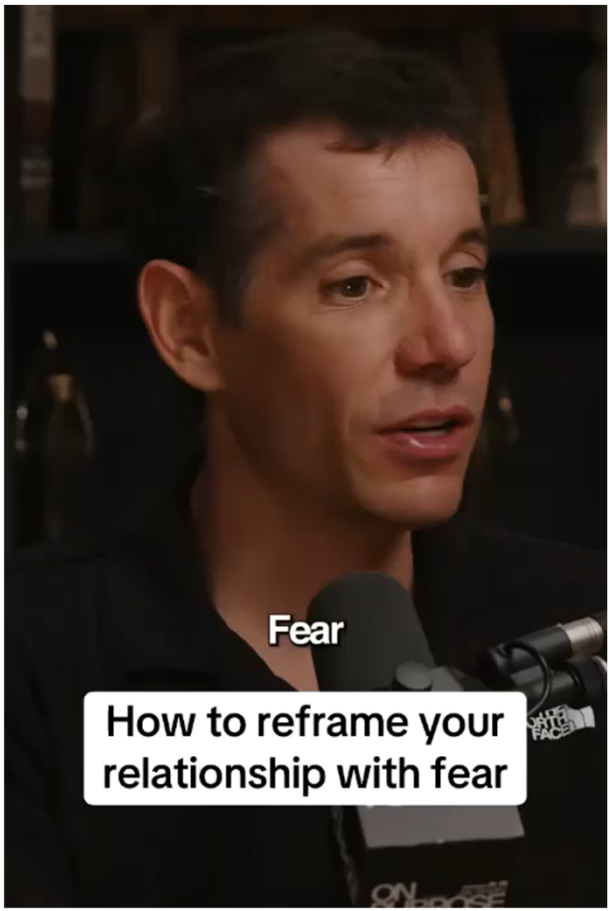
Pharmaceutical Polymers

Alex Honnold: Fear and Hunger

Free Solo of Taipei 101



Drug Delivery and Pharmaceutics

Drug Delivery Systems Terminology

Drug delivery systems

Conventional formulations, e.g., tablet, capsule, ointment, and solutions, that release most or all loaded drug(s) immediately without any control. Thus, conventional formulations are usually called "immediate release" or IR formulations.

Controlled release drug delivery systems

Newer formulations that have a built-in technology to control the drug release kinetics over time.
The term "controlled" had an additional meaning of maintaining relatively constant drug concentration in the blood over time. However, maintaining a constant drug concentration is difficult, especially for oral controlled release formulations.
The formulations are effective as long as the drug concentrations are maintained within the therapeutic index, i.e., above the minimum effective drug concentration and below the maximum safe concentration.

Controlled release drug delivery systems have also been called

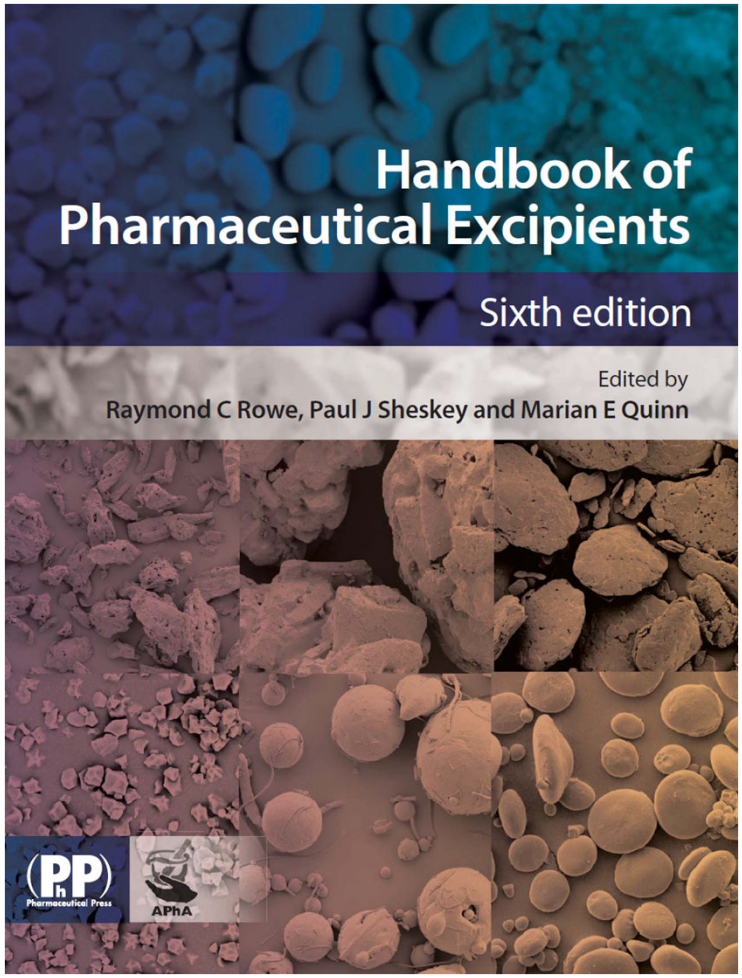
- Sustained-release Systems
- Extended-release Systems
- Delayed-release Systems
- Therapeutic Systems

Drug Delivery Systems = Drug + Everything Else (Excipients)

Excipients should be "generally regarded as safe (**GRAS**)" materials

Handbook of Pharmaceutical Excipients

Rowe 2009, Handbook of Pharmaceutical Excipients



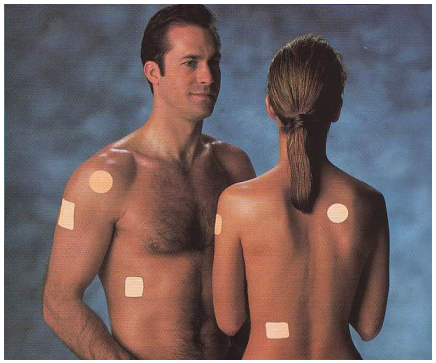
The 9th edition was published in 2020.

Controlled Release Drug Delivery Systems

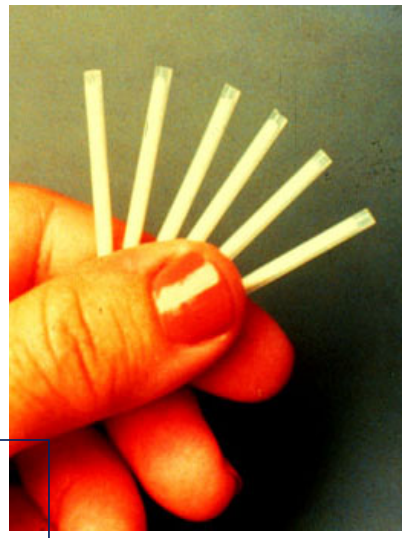
Controlled release, Sustained release, Extended release, Modified release, Programmed release

Long-Acting Systems: Less Frequent Administration → Improved patients' compliance & convenience

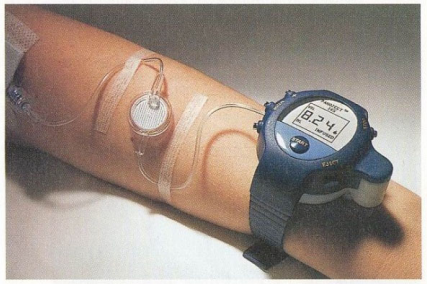
Once-a-day
Once-a-week



Once-a-month
Once-a-year



On-demand



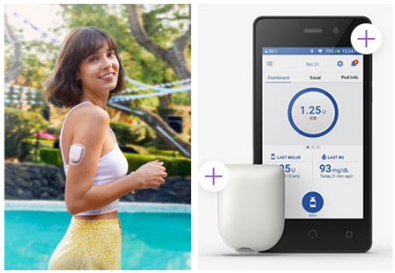
People using patient-controlled analgesia, such as the push-button Panoject (above), tend to give themselves smaller doses than they would receive in the every-four-hour system.

Norplant: Made of Silicone rubber
36 mg levonogestrel.
85 µg/day (later 30 µg/day) up to 7 years.

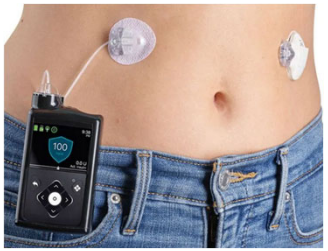
Disadvantages

Relatively high production cost
Dose dumping
Surgical operation
Difficulty in stopping drug release
Biocompatibility issue

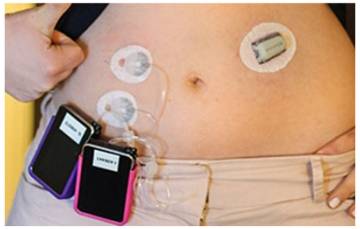
Tandem Mobi



Omnipod DASH®

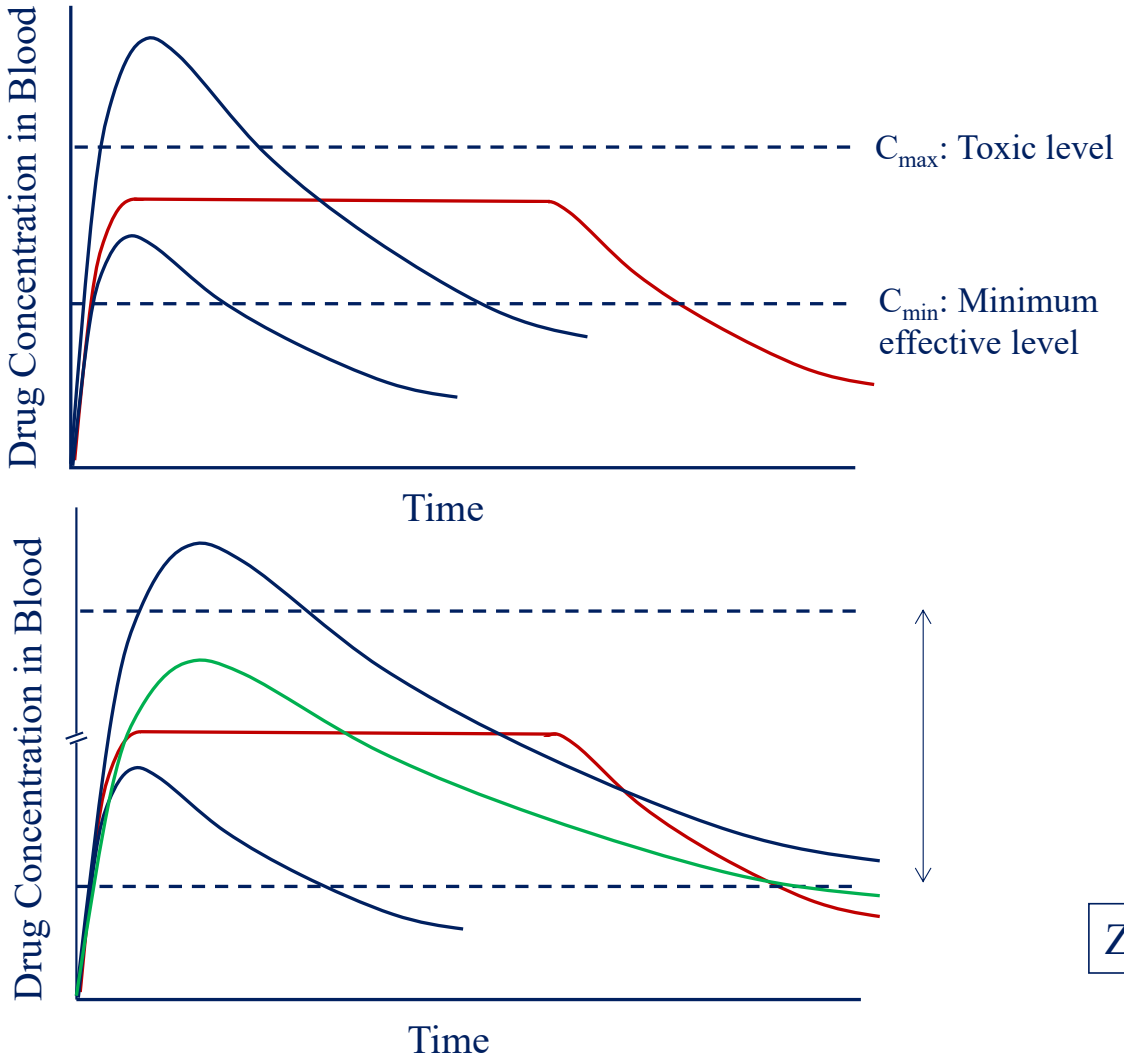


Medtronic MiniMed 780G



Beta Bionics iLet Bionic Pancreas

Rationale of Controlled Drug Delivery Systems



Therapeutic Index (TI) = C_{max}/C_{min}

TI values of selected drugs

Drug	TI
Theophylline	∞
Triphenylamine	19,000
Diphenhydramine	2,300
Chlorpheniramine	1,400
Penicillin	>100
Acetaminophen	20-40
Barbiturates	2-7
Quinidine	2-3
Digitoxin	1.5

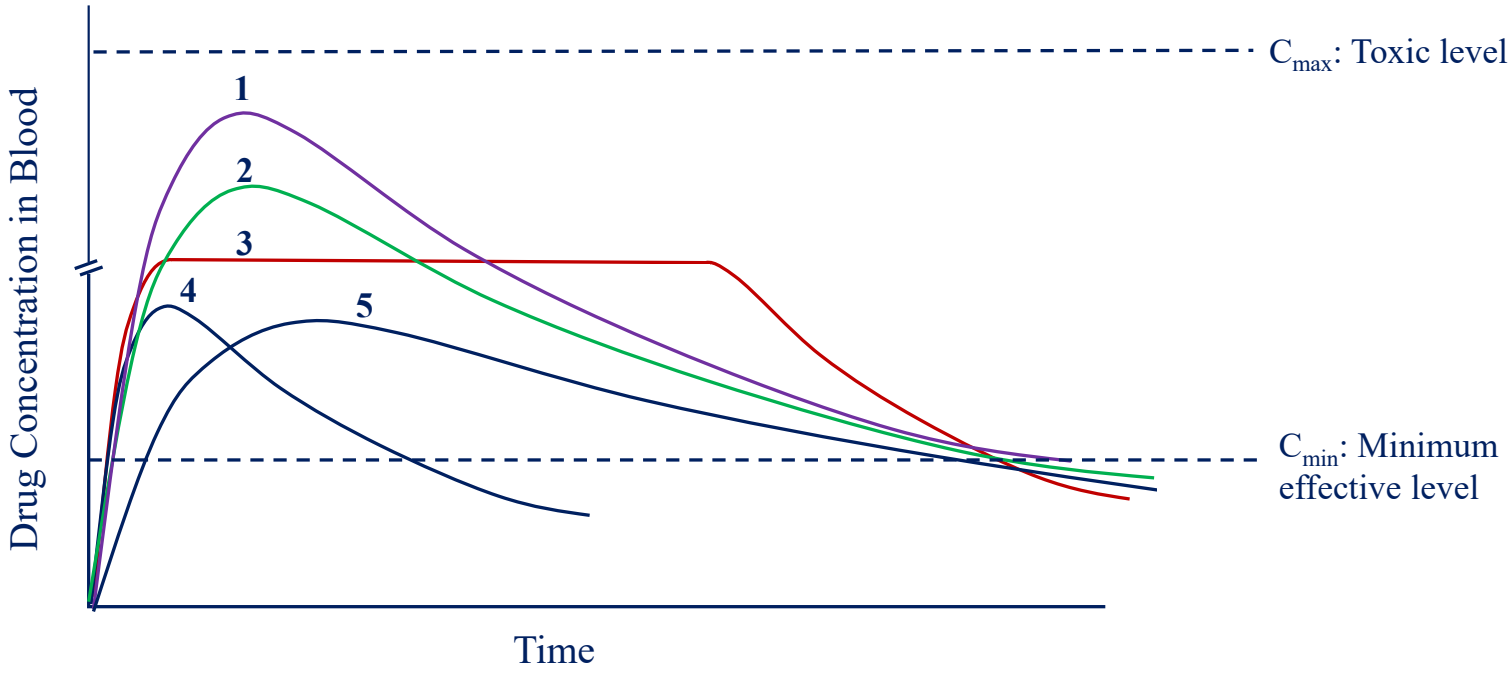
Candidate drugs for sustained release?

Zero-order release system?

Rationale of Controlled Drug Delivery Systems

Which of the following PK profiles is the best?

Theoretical answer vs. Practical answer

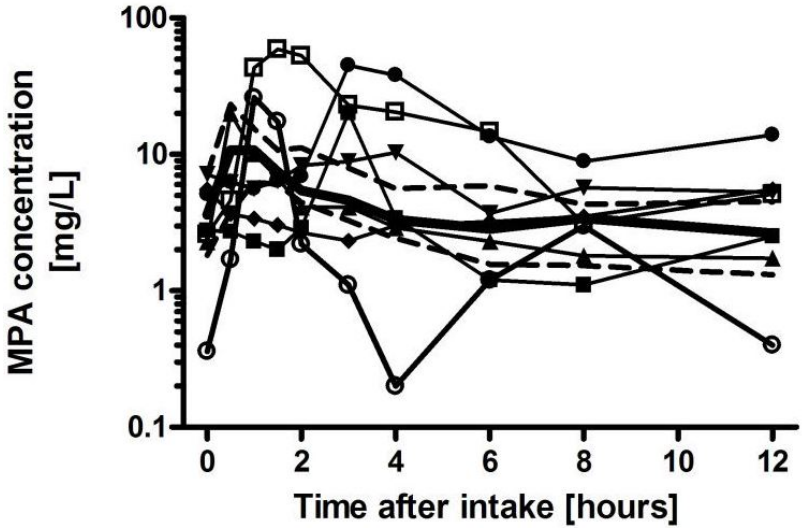


Consider how a new drug is tested and approved.

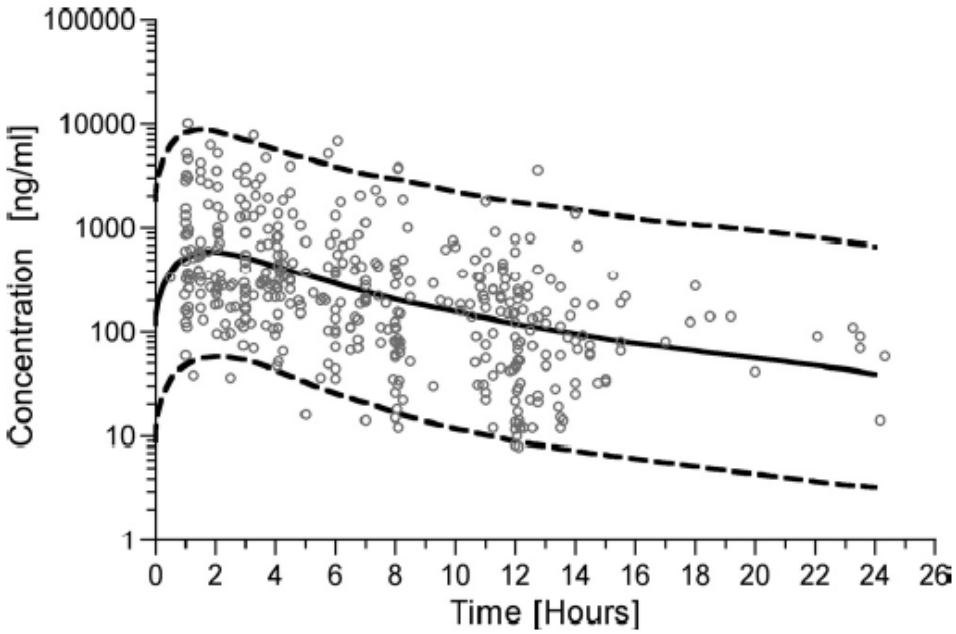
Consider what does personalized medicine mean.

Human Pharmacokinetic Variations

Any small difference in drug release behavior due to formulation changes may be insignificant.
The inter-individual variations are so significant that any small formulation changes are likely to be buried in the inter-individual variations.
Thus, the new formulation needs to be 10X better, not 100% (1X) better.



Patients on enteric-coated mycophenolate sodium (EC-MPS) showed random PK profiles (Figure 2). For the convenience of the reader, we superimposed the actual PK profiles over the percentiles of the mycophenolate mofetil profiles.
Six individual pharmacokinetic PK profiles of 6 pediatric patients with autoimmune disease on EC-MPS, superimposed on figure 1.
https://ped-rheum.biomedcentral.com/articles/10.1186/1546-0096-8-1



RAL concentrations (circles) versus time standardized for a 400-mg BID dosing in HIV and HIV individuals, with population predictions (solid line) and the 95% prediction interval (dashed lines)

Population Pharmacokinetic Analysis and Pharmacogenetics of Raltegravir in HIV-Positive and Healthy Individuals Arab-Alameddine et al. Antimicrobial Agents and Chemotherapy 56(6): 2959–2966, 2012.

Evolution of Controlled Drug Delivery Systems

1950 1960 1970 1980 1990 2000 2010 2020 2030

1952 Spansule®
Dissolution-control

1974 Ocusert®
Diffusion-control

1975 OROS®
Osmosis

1982 Delsym®
Ion exchange

1989 Lupron Depot®
PLGA Microparticle

Nanomedicine

Small Molecules

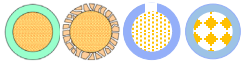
Peptide & Protein Drugs

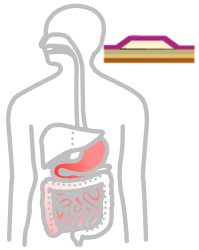
Targeting

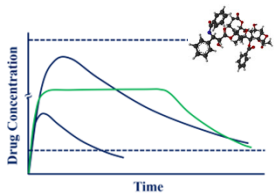
Biological Barriers

Long-Term Treatment

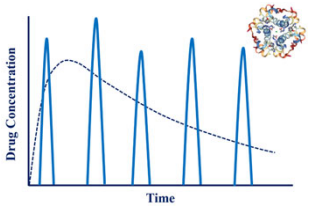
Basic Drug Delivery Mechanisms







Controlled release ≈
Sustained Release



Modulated drug delivery

Drug release kinetics controls pharmacokinetic (PK) profile → **Body controls PK profile**

1964 Liposome
(Bangosome)

1974 InFed®
Iron-Dextran Complex
(IRON DEXTRAN Injection USP)

1979 Transderm Scop®
(scopolamine)
TRANSDERMAL SYSTEM 1.5 mg

1990 Norplant®
Implant

2000 Mylotarg™
(gemtuzumab ozogamicin) for Injection
Ab-Drug Conjugate

2000 Rapamune®
Nanocrystal
(sirolimus) Tablets

2019 Rebelsus®
Oral Peptide Tablet
semaglutide tablets

1994 Taxol®
Paclitaxel in PEGylated Castor Oil

2005 Abraxane®
Paclitaxel-Albumin Complex

1990 Adagen®
(pegademase bovine) Injection
PEGylated Protein

2014 Movantik®
(naloxegol) Tablets
PEGylated naloxol

2018 Onpattro®
(patisiran) lipid complex injection
RNAi in PEGylated Lipid Nanoparticle

1995 Doxil®
PEGylated Liposome

2017 Kymriah® CAR-T Gene Therapy
(tisagenlecleucel)

2021 Comirnaty®
(COVID-19 Vaccine, mRNA)
PEGylated Lipid Nanoparticle

Pre-1950

The 1906 Pure Food and Drugs Act

The Pure Food and Drug Act (1906)

Signed by President Theodore Roosevelt in 1906.

It was commonly known as the Harvey Law.
But it had many shortcomings and became mute in 1930.

Commemorative 50th Anniversary of Pure Food and Drug Laws stamp first issued by the U.S. Postal Service on June 27, 1956

The Federal Food, Drug, and Cosmetic Act (1938)

Signed by President Roosevelt in June 1938.

New drugs have to be tested for safety before marketing, and the result has to be submitted to FDA in a new drug application (NDA).

Point: Drink a milk from a grocery → Safe

https://www.fda.gov/about-fda/fdas-evolving-regulatory-powers/part-iii-drugs-and-foods-under-1938-act-and-its-amendments

The Kefauver-Harris Amendments (1962)

Drug manufacturers must prove that their products were both safe and effective for approval.

Safety and effectiveness should consist of "adequate and well-controlled" scientific experiments carried out by "experts qualified by scientific training."

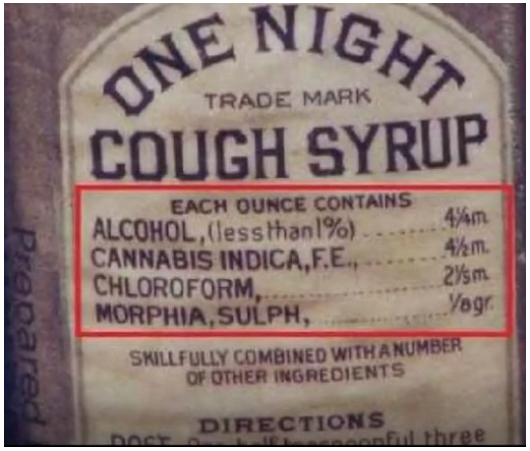
Thalidomide devastation

http://www.fda.gov/ForConsumers/ConsumerUpdates/ucm322856.htm

The Food and Drug Administration (FDA)

Medicine Shouldn't Be A Luxury

A patent medicine in 1800s.



TikTok @_chelittaditt

Forbes Jan. 2020

American Experience: The Poison Squad

'The Poison Squad' tells the story of government chemist Dr. Harvey Wiley who, determined to banish these dangerous substances from dinner tables, took on the powerful food manufacturers and their allies. (Season 32, Episode 2).

https://www.pbs.org/video/the-poison-squad-5sf93j/

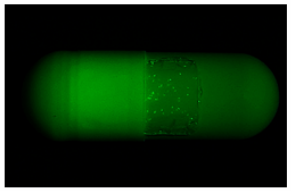
PurdueTODAY

January 28, 2020 Current web edition

ADDITIONAL NEWS

PBS show to feature work of one of Purdue's first faculty members

"The Poison Squad," a PBS documentary airing at 9 tonight (Jan. 28), tells the story of government chemist Dr. Harvey Wiley, one of Purdue's first chemistry professors and Indiana's first state chemist. Wiley worked to regulate the safety of food and drugs and is known as the "Father of the Pure Food and Drugs Act." In 1901, Wiley set out to prove Americans were being harmed by chemicals in food and organized volunteers for human trials to test the effects of chemical food preservatives.

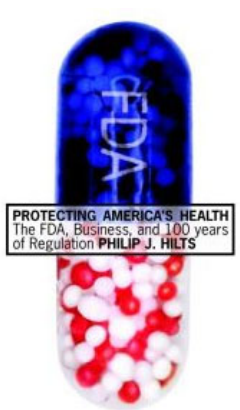


Edible 'security tag' to protect drugs from counterfeit

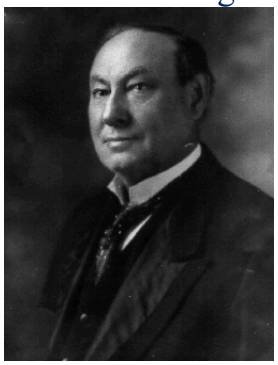
Manufacturing prescription drugs with distinct markings, colors, shapes or packaging isn't enough to protect them from counterfeiting, U.S. Drug Enforcement Administration reports have shown. Purdue researchers are aiming to stump counterfeiters with an edible "security tag" embedded into medicine. To imitate the drug, a counterfeiter would have to uncrack a complicated puzzle of patterns not fully visible to the naked eye.

The Food and Drug Administration (FDA)

Protecting America's Health: The FDA, Business, and One Hundred Years of Regulation

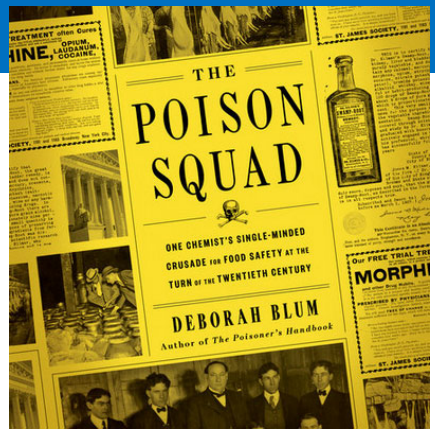


Philip J. Hilts. 2003



Dr. Harvey Washington Wiley: Creator of the FDA. Professor at Purdue University.

The Poison Squad: One Chemist's Single-Minded Crusade for Food Safety at the Turn of the Twentieth Century



"By the end of nineteenth century, food was dangerous. Lethal, even. “Milk” might contain formaldehyde, most often used to embalm corpses. Decaying meat was preserved with both salicylic acid, a pharmaceutical chemical, and borax, a compound first identified as a cleaning product.

This was not by accident; food manufacturers had rushed to embrace the rise of industrial chemistry, and were knowingly selling harmful products. Unchecked by government regulation, basic safety, or even labelling requirements, they put profit before the health of their customers. By some estimates, in New York City alone, thousands of children were killed by “embalmed milk” every year. Citizens–activists, journalists, scientists, and women’s groups–began agitating for change. But even as protective measures were enacted in Europe, American corporations blocked even modest regulations. Then, in 1883, Dr. Harvey Washington Wiley, a chemistry professor from Purdue University, was named chief chemist of the agriculture department, and the agency began methodically investigating food and drink fraud, even conducting shocking human tests on groups of young men who came to be known as, 'The Poison Squad.'"

https://www.penguinrandomhouse.com/books/312067/the-poison-squad-by-deborah-blum/9781594205149/

Wiley and some of the first federal scientists of the Bureau of Chemistry (1906).

The first significant clinical study on the effect of food preservatives (1902). (No control group!)

The Jungle (1906)

Sinclair. "I aimed at the public's heart (workers' right), and by accident I hit it in the stomach."

Upton Sinclair : The Jungle

A NAUSEATING JOB, BUT IT MUST BE DONE
(President Roosevelt takes hold of the investigating muck-rake himself in the packing-house scandal.)

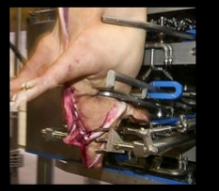
- The effects from the accusations against the meat packing industry in *The Jungle* led to investigations into the food and patent medicine industry in general.

Upton Sinclair's *The Jungle*

- Laws passed after Congress' investigation:
- ***Meat Inspection Act***
  - USDA (US Department of Agriculture)
- ***Pure Food and Drug Act***
  - FDA (Food and Drug Administration)

Criticism of Upton Sinclair's *The Jungle*

- Was Sinclair *too biased*? Was Sinclair just anti-capitalist trying to attack the meat industry? Did Sinclair *exaggerate* about what was *really* taking place in the meat-packing factories?



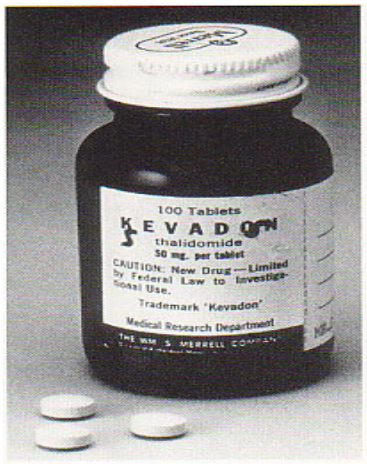
- *The Jungle's* fictitious characters tell of men falling into tanks in meatpacking plants and being ground up with animal parts, then made into "Durham's Pure Leaf Lard."
- Historian Stewart H. Holbrook argues this was nonsense. Sinclair's *The Jungle* was far from reality:
  - ***"The grunts, the groans, the agonized squeals of animals being butchered, the rivers of blood, the steaming masses of intestines, the various stenches . . . were displayed along with the corruption of government inspectors and, of course, the callous greed of the ruthless packers."***

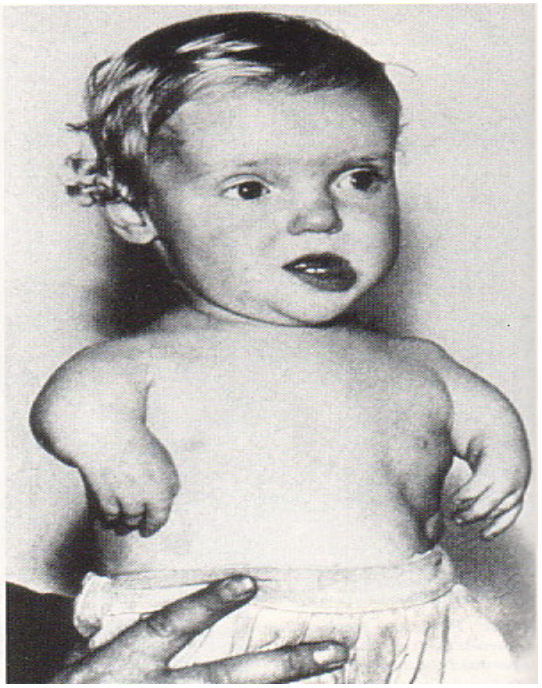
Criticism of Upton Sinclair's *The Jungle*

- When the sensational accusations of *The Jungle* became worldwide news, foreign purchases of American meat dropped by *HALF!* American meat packing companies were losing a huge market share.
- The meatpackers looked for new regulations to give their markets a calming sense of security so the public (and consumers across the world) would trust and buy their meat instead of fearing what was in it.
- Congressional hearings for what became the Meat Inspection Act of 1906 were held by Congressman James Wadsworth's Agriculture Committee:
- *"Knowing that a new law would allay public fears fanned by The Jungle, bring smaller competitors under regulation, and put a newly-laundered government stamp of approval on their products, the major meat packers strongly endorsed the proposed act and only argued over who should pay for it."*

https://www.slideshare.net/iRawrPanda/upton-sinclair-and-critics-of-the-jungle

The Thalidomide Incidence





Above: *Kevadon, also known as thalidomide. It was sold chiefly outside the United States as a sedative despite a lack of testing to determine if it was safe. It caused birth defects when taken in the early months of pregnancy, and led to thousands of cases of premature death and, most famously, a fetal disability in which limbs were stunted. The FDA refused to approve it without better safety data.*

Thalidomide's horrifying effects on newborns became known in 1962.
Distribution of two million tablets by Merrell for investigational use.

Frances Kelsey:
Medical officer at FDA Refusal to allow NDA of thalidomide based on insufficient safety data.

History Repeats Itself

Different subjects but the same cycle:

Ignorance, Outrage, & New law protecting consumers

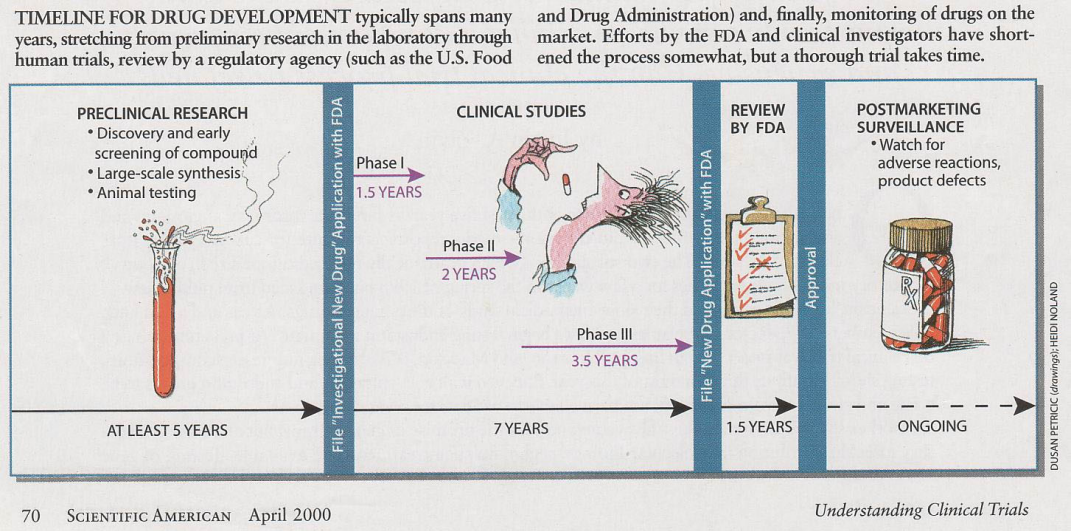
Industries for profit

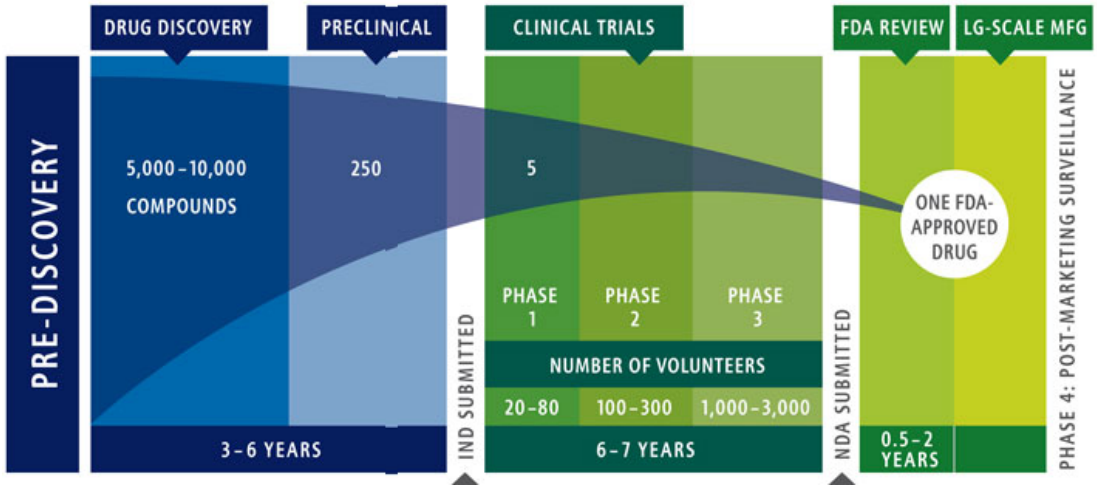
- **Food industry**
  - **Livestock (water consumption and methane (CH_4) emission)**
  - **Fishery & Fishing industry**
- **Tobacco industry**
- **Opioid pain killers**
- **Plastics industry**
- -
- -
- -

The Danger of Hypes: History rhymes

Importance of the Food & Drug Administration

Safety and Efficacy of Drug Delivery Systems





From drug discovery through FDA approval, developing a new medicine takes at least 10 years on average and costs an average of $2.6 billion, including the cost of the many potential medicines that do not make it through to FDA approval. Less than 12% of the candidate medicines that make it into Phase 1 clinical trials will be approved by the FDA.

Drug Potency

IND: Investigational new drug application
NDA: New drug application
BLA: Biologics license application

Source: PhRMA adaption based on Tufts Center for Study of Drug Development (CSDD) Briefing: Cost of developing a new drug. Nov. 2014. Tufts CSDD & School of Medicine and US FDA Infographic.
Drug Approval Process: http://www.fda.gov/downloads/Drugs/ResourcesForYou/consumers/UCM284393.pdf
http://www.phrma.org/advocacy/research-development/clinical-trials
https://publicpolicy.wharton.upenn.edu/live/news/1764-debate-over-the-priority-review-voucher/for-students/blog/news.php

FDA Drug Approval Process

What is a drug as defined by the FDA? A drug is any product that is intended for use in the diagnosis, cure mitigation, treatment , or prevention of disease; and that is intended to affect the structure or any function of the body.

PRE-CLINICAL: Drug Sponsor's Discovery and Screening Phase

1 **Drug Developed**

Drug sponsor develops a new drug compound and seeks to have it approved by FDA for sale in the United State.

Animals Tested

Sponsor must test new drug on animals for toxicity. Multiple species are used to gather basic information on the safety and efficacy of the compound being investigated/researched.

2 **IND Application**

The sponsor submits an Investigational New Drug (IND) application to FDA based on the results from initial testing that include the drug's composition and manufacturing, and develops a plan for testing the drug on humans.

http://www.fda.gov/Drugs/ResourcesForYou/Consumers/ucm295473.htm

CLINICAL: Drug Sponsor's Clinical Studies/Trials

3 **Phase 1: 20-80**

The typical number of healthy volunteers used in Phase 1; this phase emphasizes safety. The goal here in this phase is to determine what the drug's most frequent side effects are and often, how the drug is metabolized and excreted.

4 **Phase 2: 100s**

The typical number of patients used in Phase 2; this phase emphasizes effectiveness. The goal here is to obtain preliminary data on whether the drug works in people who have certain disease condition. Short-term side effects are studied.

At the end of Phase 2, FDA and sponsors discuss how large-scale studies in Phase 3 will be done.

5 **Phase 3: 1000s**

The typical number of healthy volunteers used in Phase 3. These studies gather more information about safety and effectiveness, study different populations and different dosages, and uses the drug in combination with other drugs.

FDA Drug Approval Process

Who reviews new drug submissions? A team of CDER physicians, statisticians, chemists, pharmacologists, and other scientists review the drug sponsor's data and proposed labeling of drugs.

PDUFA
Prescription Drug User Fee Act

Since the PDUFA was passed in 1992, more than 1,000 drugs and biologics have come to the market, including new medicines to treat cancer, AIDS, cardiovascular disease, and life-threatening infections.

PDUFA has enabled the Food and Drug Administration to bring access to new drugs as fast or faster than anywhere in the world, all while maintaining the same thorough review process. Under PDUFA, drug companies agree to pay fees that boost FDA resources, and FDA agrees to time frames for its review of new drug applications.

NDA REVIEW: FDA's New Drug Application (NDA) Review

6 **Review Meeting**
FDA meets with a drug sponsor prior to submission of a New Drug Application.

7 **NDA Application**
The drug sponsor formally asks FDA to approve a drug for marketing in the U.S. by submitting an NDA. An NDA includes all animal and human data and analyses of the data, as well as information about how the drug behaves in the body and how it is manufactured.

8-9 **Application Reviewed**
After an NDA is received, FDA has 60 days to decide whether to file it so it can be reviewed. If FDA files the NDA, the FDA review team is assigned to evaluate the sponsor's research on the drug's safety and effectiveness.

10 **Drug Labeling**
FDA reviews the drug's professional labeling and assures appropriate information is communicated to health care professionals and consumers.

FASTER APPROVALS
The Accelerated Approval program. The Fast Track program.

Example
FDA Fast-Tracks Experimental Ebola Drug Zmapp
(http://www.nbcnews.com/storyline/ebola-virus-outbreak/ebola-drug-zmapp-gets-fda-fast-track-n429156)
(https://www.statnews.com/2016/10/12/ebola-zmapp-trial-results/)
Promising Ebola Drug ZMapp: The Real Lessons of an Inconclusive Study
(http://www.livescience.com/56468-ebola-drug-zmapp-study-inconclusive.html)

COVID-19 Vaccine Deevelopment

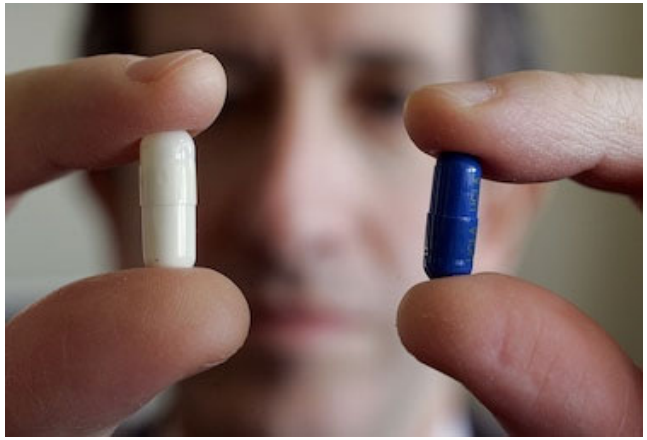
POST-MARKETING: FDA's Post-Approval Risk Assessment Systems

Phase 4
Because it's not possible to predict all of a drug's effects during clinical trials, monitoring safety issues after drugs get on the market is critical. The role of FDA's post-marketing safety system is to detect serious unexpected adverse events and take definitive action when needed.

http://www.fda.gov/Drugs/ResourcesForYou/Consumers/ucm295473.htm

Clinical Studies: Efficacy Better Than Placebo

Most of the trials done so far on open-label placebos have been small, but the results are starting to add up. A systematic review published last year in Scientific Reports evaluated 13 studies with nearly 800 participants and concluded that open-label placebos exhibit significant positive effects. The reviewers cautioned, though, that in the early stages of research in any field, positive studies are more likely to be published than those not supporting the technique. Still, the unexpected effect has many medical experts intrigued.



The use of placebos in clinical trials really took off in the 1960s, after Congress passed an amendment that authorized the U.S. Food and Drug Administration to require pharmaceutical companies to prove that new drugs were not just safe but also effective. Clinical trials comparing a medicine to a harmless placebo became the accepted way to do that, scientists noted in the New England Journal of Medicine on the amendments' 50th anniversary.
In traditional clinical trials, participants are never informed whether they are receiving the drug or the placebo. Scientists evaluating the trial data are not told either, so the results are supposed to be more directly comparable and less likely to introduce bias.

The fact that it's prescribed by a physician is also key, experts say. "A placebo isn't about the pill. It's the ritual of the pill," Kaptchuk says.

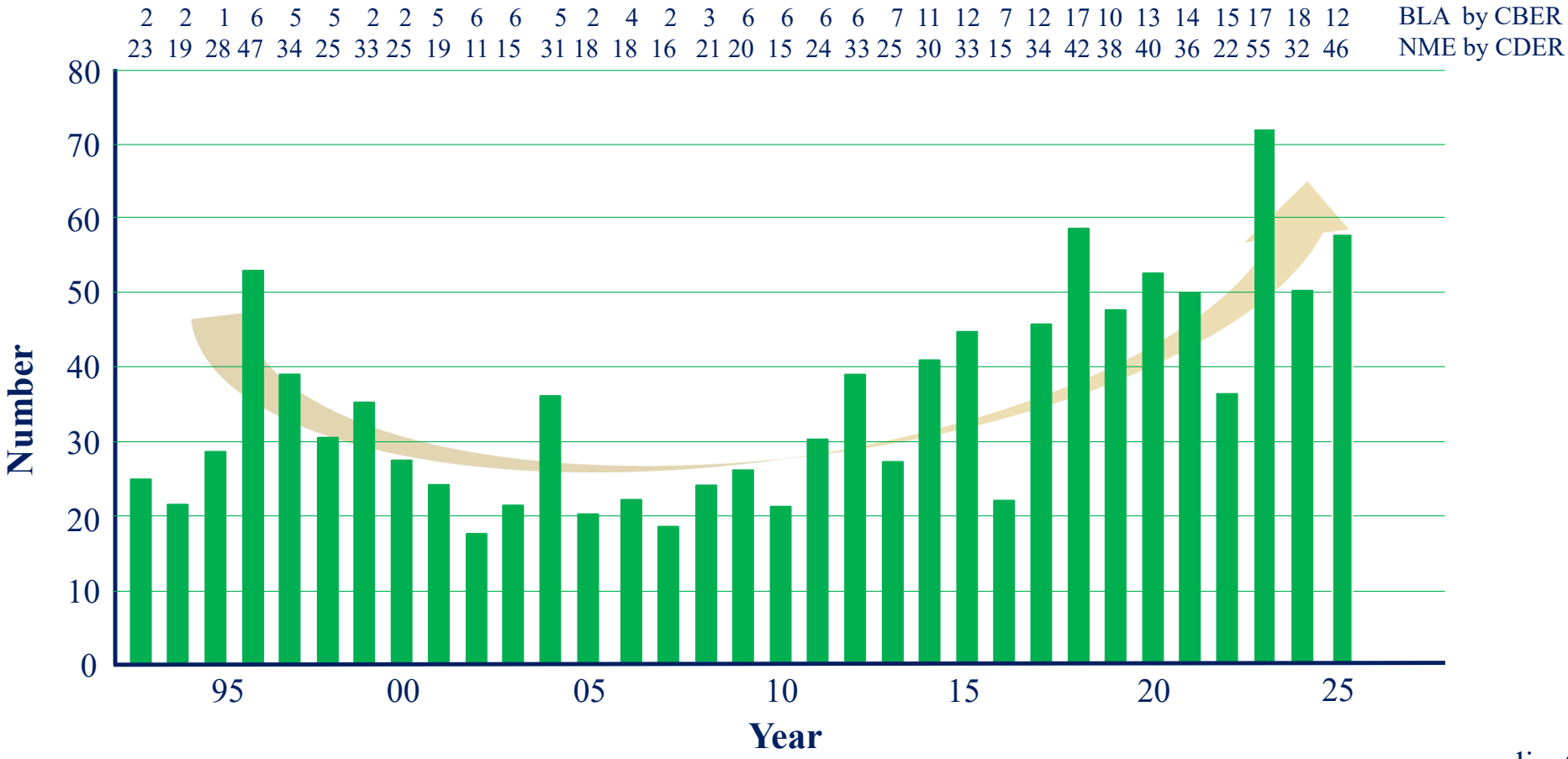
"This is not about believing you're going to get better," Kaptchuk surmises. "In my opinion, this is about the body knowing something that's not conscious."

"The mind plays such an important role in patient recovery," Krystal says. Like all placebos, open-label ones take advantage of the bond between doctors and patients that is "one of the most special and unique connections among people in our society."

Landau 2022, Why a placebo can work—even when you know it's fake

https://www.nationalgeographic.com/magazine/article/why-a-placebo-can-workeven-when-you-know-its-fake?rid=FF526C1F1B0738788B420FE1D0034350&cmpid=org%3Dngp%3A%3Amc%3Dcrm-email%3A%3Asrc%3Dngp%3A%3Acmp%3Deditorial%3A%3Aadd%3DHealth_20220925&loggedin=true

FDA Approvals of Novel Drugs



FDA's Center for Drug Evaluation and Research (CDER) evaluates new drugs before they can be sold.

The center's evaluation not only prevents quackery, but also provides doctors and patients the information they need to use medicines wisely. CDER ensures that drugs, both brand-name and generic, are effective and their health benefits outweigh their known risks.

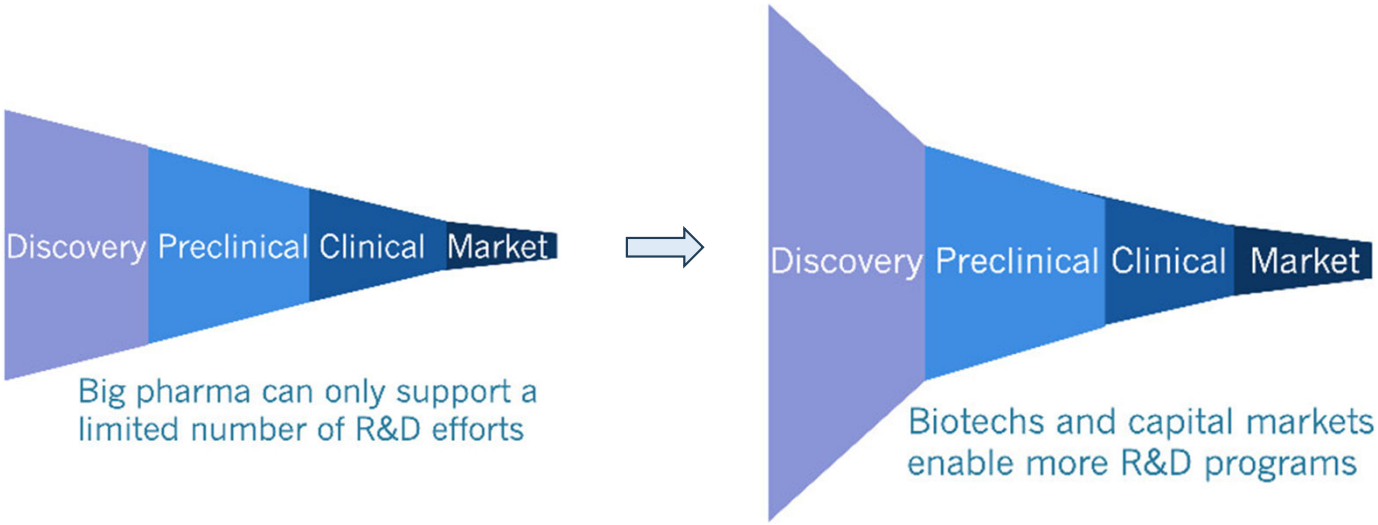
http://www.fda.gov/Drugs/DevelopmentApprovalProcess/DrugInnovation/ucm483775.ht
https://www.fda.gov/drugs/developmentapprovalprocess/druginnovation/ucm592464.htm

application

NME: New molecular entity

http://www.fda.gov/Drugs/ResourcesForYou/Consumers/ucm295473.htm
https://www.fda.gov/drugs/new-drugs-fda-cders-new-molecular-entities-and-new-therapeutic-biological-products/novel-drug-approvals-2021

FDA Approvals of Novel Drugs



Advantages of small companies:

- Cost advantage
- Focus: Doggedness & No fail early mentality
- Organizational alignment: The same goal

Future R&D productivity

- Difficulty of raising capital.
- Uncertain funding from the government.

Reynolds 2025, The new paradigm in pharma R&D

Difficulties in Developing New Drugs

Why is it So Difficult to Develop a New Drug?

Drugs don't differentiate:
Not enough sound therapeutic hypotheses!

No rationale in picking targets based on human biology

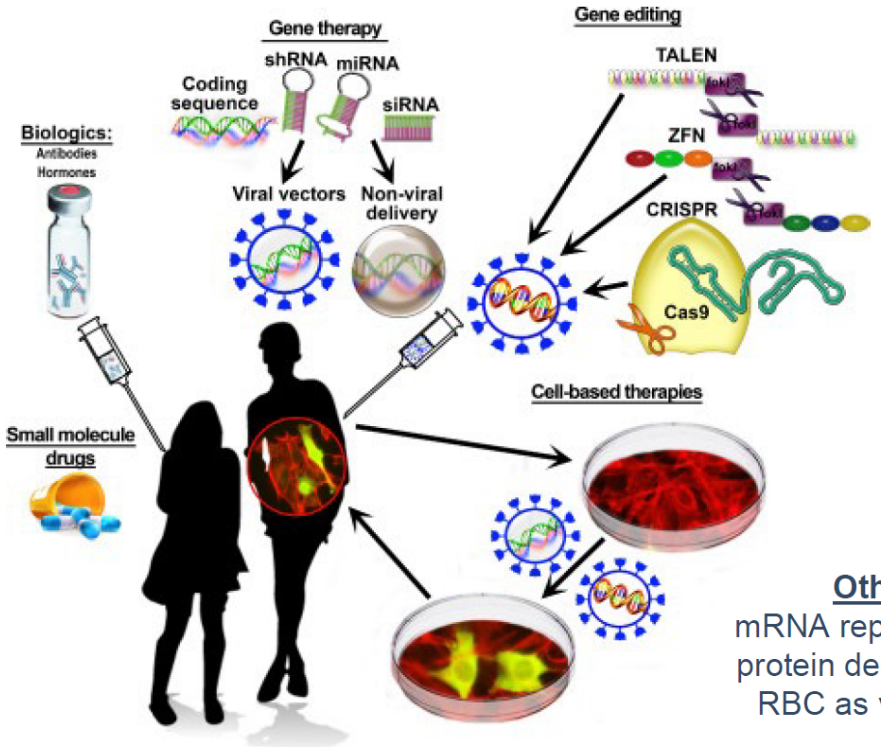
No human phenotype for drug efficacy testing

Incomplete understanding of biological function or molecular mechanism of disease-associated variants, genes & pathways

Conventional modalities (e.g., small molecules, monoclonal antibodies) modulate <20% of targets

New modalities are desperately needed, but today are limited by delivery and pharmacological properties

Trial and Error Approach



Precision medicine: patient subsets for whom therapeutic intervention works better

http://www.nationalacademies.org/hmd/~/media/Files/Activity%20Files/Research/DrugForum/2017%20MAR%208/Plenge%20-%20Session%20IV.pdf

Targeting vs. Targeting

Targeted Therapy (or Targeting Therapy) vs. Targeted Drug Delivery (or Drug Targeting)

The term "targeted drug delivery" (or "drug targeting") used in drug delivery is distinct from "targeted therapy" (or "targeting therapy") that is frequently used in drug discovery. Targeted drug delivery refers to the predominant accumulation of a drug within a target zone, which is independent of the method and route of drug administration. On the other hand, targeted therapy, also known as targeted medicine, refers to a specific interaction between a drug and its receptor at the molecular level. Effective targeted drug delivery systems require four key requirements: retention, evasion, targeting, and release. For formulations intended for i.v. administration, this means efficient drug loading into a suitable delivery vehicle, sufficient residence in the circulation to reach the intended sites of the body, retention by specific characteristics within these sites (i.e., targeting), and drug release at the intended site within a timeframe that allows for the effective function of the drug. Obviously, drug targeting to specific sites in the body requires different delivery systems depending on the drug delivery route selected.

True targeted drug delivery is still beyond our grasp, but it is probably the single most important property that drug delivery systems should acquire for treating cancers and certain other diseases, where it is crucial to place a drug selectively at a specific site in the body. The information necessary to achieve effective drug targeting may already exist, but we are currently unable to extract the answers from all the available information. By understanding our current misunderstandings on targeted drug delivery, we will be in a better position to discover the solutions for true drug targeting. The current concept of ligand-modified PEGylated nanoparticles as a "magic bullet" needs to be modified. It simply presents an inaccurate picture of a very complicated problem

A magic bullet is for targeted therapy, not for targeted drug delivery.

Bae 2011, Targeted drug delivery to tumors: myths, reality, and possibility

Magic Bullet Against Enemy

Paul Ehrlich's Magic Bullet

Selective targeting to a bacterium without affecting other organisms.

↓

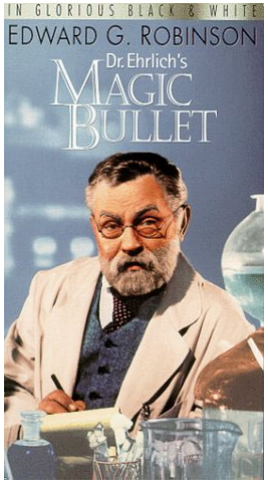
Selective killing

A drug that goes straight to its intended cell-structural targets to treat disease.

↓

interacts with

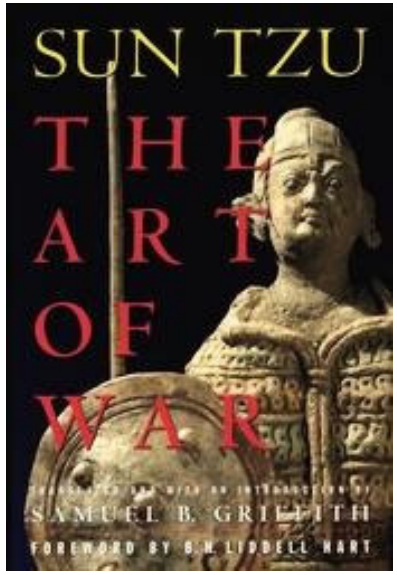
Nobel Prize 1908



The Art of War (孫子兵法)

(Sūn Zu Bīng Fǎ)

知己知彼 百戰百勝



The Art of War against Diseases

We may know the properties of the drug delivery systems in vitro and in vivo.

But we do not know heterogeneity and dynamic states of our bodies and the diseases!

Alzheimer's Disease

Science and technology

The Economist July 25th 2015

Dementia

Flattening the slope

A glimmer of hope in the fight against a dreadful illness

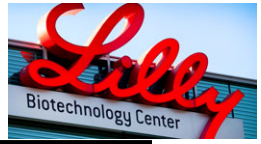
ALZHEIMER'S disease is incurable, and only barely treatable. Drugs such as Aricept bring temporary relief, but nothing halts its onward march. There was therefore a lot of excitement, among researchers and journalists alike, in the lead-up to a lecture given on July 22nd at the Alzheimer's Association International Conference, in Washington, DC. The talk was entitled "Delayed Start Studies in the Assessment of Potential Disease Modifying Effect". Translated into English, that meant the researchers presenting the paper, who work for Eli Lilly, a big pharmaceutical company, thought they had come up with something which slows down the illness's progression.

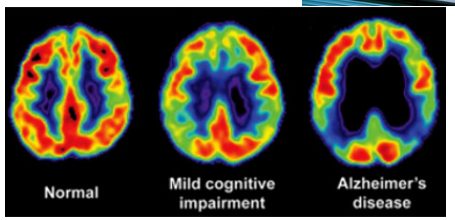
Their something is an antibody, called solanezumab by its inventors, that sticks to beta amyloid. This is one of the proteins which contribute to the plaques and tangles of matter in the brain that are characteristic of the disease. The researchers hoped, when they began the study, that solanezumab might slow down plaque formation and give a patient extra years of lucidity.

When Lilly tested the drug in 2012, they found little evidence of success—except in those with mild, early-onset Alzheimer's, for whom there were hints that the progression of the disease had been slowed. But by extracting this group from the rest, and concentrating on them, the firm's scientists have discovered something more hopeful.

Their delayed-start trial worked like this. Three and a half years ago, the 1,300 qualifying patients were divided into two groups. One lot were put on solanezumab immediately. The others were given a placebo for the trial's first 18 months, and thereafter switched to the real thing, which they have now been taking for two years.

In cognitive tests that use a quantitative scale of dementia's effects, those in the delayed group fell behind the others in the months when they were on the placebo. Once they switched to the drug, their rate of decline slowed to match that of those who had been on treatment since the beginning. The antibody appeared, in other words, to be slowing the disease's progress. This is nowhere near a cure. It may, however, point the way to one. Perhaps a different antibody, or a combination, would have a greater effect. ■





https://www.nytimes.com/2016/11/23/health/eli-lillys-experimental-alzheimers-drug-failed-in-large-trial.html?_r=0

Lilly Announces Top-Line Results of Solanezumab Phase 3 Clinical Trial

INDIANAPOLIS, Nov. 23, 2016 /CNW/ -- Eli Lilly and Company (NYSE: LLY) today announced that solanezumab did not meet the primary endpoint in the EXPEDITION3 clinical trial, a phase 3 study of solanezumab in people with mild dementia due to Alzheimer's disease (AD).

Patients treated with solanezumab did not experience a statistically significant slowing in cognitive decline compared to patients treated with placebo (p=.095), as measured by the ADAS-Cog_{14} (Alzheimer's Disease Assessment Scale-Cognitive subscale). https://investor.lilly.com/releasedetail.cfm?ReleaseID=1000871

Solanezumab is a humanized monoclonal IgG1 antibody directed against the mid-domain of the Aβ peptide. It recognizes soluble monomeric, not fibrillar, Aβ. The therapeutic rationale is that it may exert benefit by sequestering Aβ, shifting equilibria between different species of Aβ, and removing small soluble species of Aβ that are directly toxic to synaptic function. In preclinical research, a single injection of m266, the mouse version of solanezumab, reversed memory deficits in APP-transgenic mouse models while leaving amyloid plaques in place, raising the prospect of targeting the soluble pool of Aβ

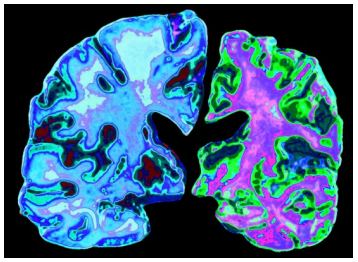
http://www.alzforum.org/therapeutics/solanezumab

Failed Alzheimer's trial does not kill leading theory of disease

The drug, and others based on the 'amyloid hypothesis', are still being tested in other, different trials.

Alison Abbott & Elie Dolgin.

Nature 540: 15-16, 2016

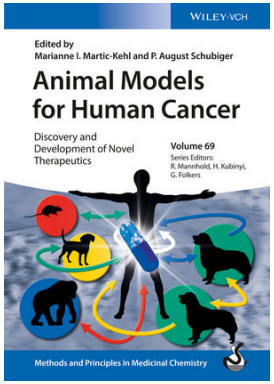


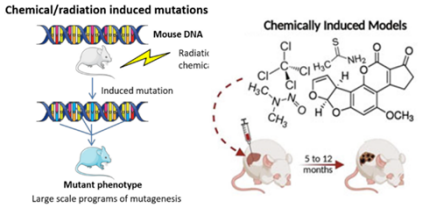
Brain of healthy 70-year-old (left) compared with brain of 70-year-old with Alzheimer's (right).

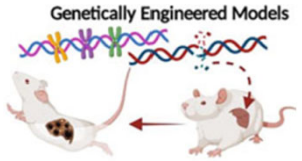
http://www.nature.com/news/failed-alzheimer-s-trial-does-not-kill-leading-theory-of-disease-1.21045

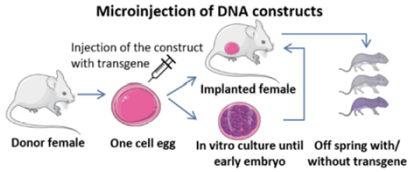
Animal Studies

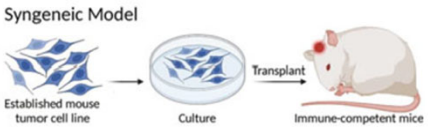
Animal Models for Cancer Studies

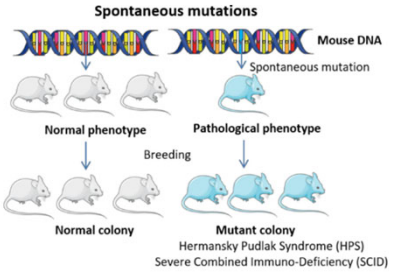


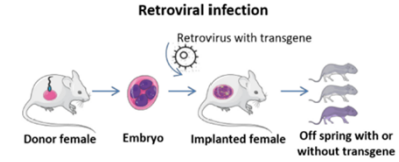


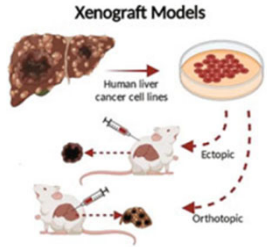


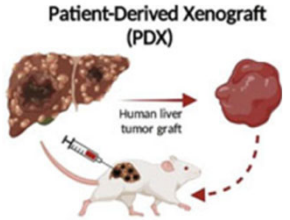








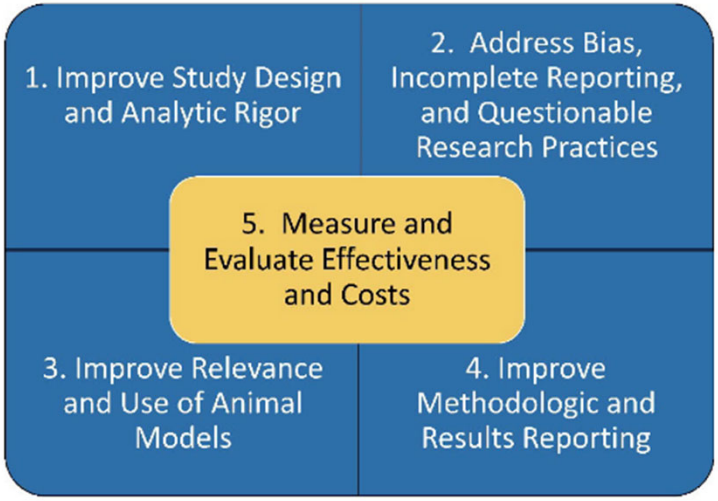




Commonly used animal models for cancer studies.
(Dhumal et al., Preclinical animal models for cancer research and drug discovery, in Bose & Chaudhari, Eds., Unravelling Cancer Signaling Pathways. 2019.)
https://www.eara.eu/why-are-animals-used-cancer-research

Das et al., Importance of animal models in the field of cancer research & Karakurt et al., Animal model of human cancer: malignant lymphoma/ colon cancer/lung cancer/liver cancer/brain tumors/skin cancer (in Pathak 2023, Handbook of Animal Models and its Uses in Cancer Research)

Animal Models



Improving the translatability of animal models

ACD Working Group on Enhancing Rigor, Transparency and Translatability in Animal Research Report, 2021

- Advised how NIH can help researchers improve rigor, transparency, and reproducibility of animal research
- Overarching goals
  - o Increase confidence in quality and applicability of research
  - o Ensure animal subjects used with consideration of ethics and harm-benefit analysis

NIH 2021, ACD working group on enhancing rigor, transparency, and translatability in animal research

Elaine A. Ostrander, Ph.D.
Chief & NIH Distinguished Investigator
Cancer Genetics and Comparative Genomics Branch

Definition: An animal model is a non-human species used in biomedical research because it can mimic aspects of **a biological process or disease** found in humans. Animal models (e.g., mice, rats, zebrafish and others) are sufficiently like humans in their anatomy, physiology or response to a pathogen that researchers can extrapolate the results of animal model studies to better understand human physiology and disease. By using animal models, researchers can **perform experiments that would be impractical or ethically prohibited with humans**. --- Overall, animal models have proven valuable in studies of nearly every human condition.

(https://www.genome.gov/genetics-glossary/Animal-Model#)

How to Improve Animal Models for Better Treatment?

It's Not the Animal Model, Inadequate.
It's the Human Use, Inadequate.

Much of the published animal data on nanomedicine is irrelevant to clinical translation.

- Our interpretation of the animal data is often too optimistic.
- Most animal data are presented in a highly positive way to increase their values.
- Only positive results of animal studies are published.
- One common manifestation of cancer nanomedicine is the use of saline solutions as a control.

Publishing negative results is very difficult, making animal models seemingly unsuitable for studying cancer nanomedicine.

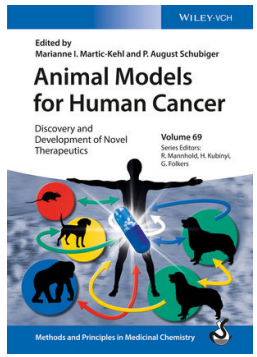
5

How to End Selective Reporting in Animal Research

Gerben ter Riet and Lex M. Bouter

5.1 Introduction

Would scientific progress not be a lot swifter and cheaper if we published, in some convenient format, all results from our negative studies too? Although convincing evidence is not available, we think the answer would be affirmative. New empirical results appear daily, but it can sometimes take years for *knowledge* to emerge. Isolated studies may be important, but almost all deeper scientific insights evolve at the meta-level; that is, at the level of collections of similar studies around a particular scientific question. Since the 1980s, in clinical medicine and public health, systematic reviews (often including a meta-analysis) of the literature have been increasingly employed to produce ("meta-level") *knowledge* [1]. These systematic reviews ought to be updated when a new piece of evidence comes along. The crucial role of integration of new findings with existing ones is not always appreciated in animal experimental work, although its justification was eloquently expressed over a century ago:



How to End Selective Reporting in Animal Research
Gerben ter Riet and LexM. Bouter
(Martic-Kehl 2016, Animal Models for Human Cancer)

Roadmap to Reducing Animal Testing

Roadmap to Reducing Animal Testing in Preclinical Safety Studies

There is growing scientific recognition that animals do not provide adequate models of human health and disease. Over 90% of drugs that appear safe and effective in animals do not go on to receive FDA approval in humans predominantly due to safety and/or efficacy issues. Animal-based data have been particularly poor predictors of drug success for multiple common diseases including cancer, Alzheimer's and inflammatory diseases. Some medications which are generally recognized safe in humans, such as aspirin, may have never passed animal testing. Conversely, some compounds which have appeared safe in animal models have been lethal in human trials. These examples highlight basic physiologic differences between humans and other animal species.

Due to the limitations of animal testing as well as ethical concerns about animals testing, there has been increased focus within the scientific community on New Approach Methodologies (NAMs). NAMs encompass *in vitro* human-based systems, *in silico* modeling, and other innovative platforms that can collectively evaluate immunogenicity, toxicity, and pharmacodynamics in humans and provide an opportunity to improve the predictive relevance of preclinical drug testing while reducing or replacing animal use. NAMs also have enormous cost saving potential.

New Approach Methodologies (NAMs)

- In Vitro Human-Derived Systems (Organoids and Microphysiological Systems)
- In Silico Tools and Computational Modeling
  - ML and AI Predictive Models
  - Quantitative Systems Pharmacology (QSP) and Modeling of Biological Pathways
  - Bioinformatics and In silico Off-target Screening

Other Innovative Platforms

- Ex vivo Human Tissues
- High-Throughput Cell-Based Screening
- Microdosing and Imaging in Human Volunteers
- Refined In Vivo Methods (for transition)

FDA 2025, Roadmap to reducing animal testing in preclinical safety studies

FDA: Phasing Out Animal Testing Requirement

https://www.fda.gov/news-events/press-announcements/fda-announces-plan-phase-out-animal-testing-requirement-monoclonal-antibodies-and-other-drugs

FDA Announces Plan to Phase Out Animal Testing Requirement for Monoclonal Antibodies and Other Drugs (April 10, 2025)

Today, the U.S. Food and Drug Administration is taking a groundbreaking step to advance public health by replacing animal testing in the development of monoclonal antibody therapies and other drugs with more effective, human-relevant methods. The new approach is designed to improve drug safety and accelerate the evaluation process, while reducing animal experimentation, lowering research and development (R&D) costs, and ultimately, drug prices.

The FDA's animal testing requirement will be reduced, refined, or potentially replaced using a range of approaches, including AI-based computational models of toxicity and cell lines and organoid toxicity testing in a laboratory setting (so-called New Approach Methodologies or NAMs data). Implementation of the regimen will begin immediately for investigational new drug (IND) applications, where inclusion of NAMs data is encouraged, and is outlined in a roadmap also being released today. To make determinations of efficacy, the agency will also begin use pre-existing, real-world safety data from other countries, with comparable regulatory standards, where the drug has already been studied in humans.

"For too long, drug manufacturers have performed additional animal testing of drugs that have data in broad human use internationally. This initiative marks a paradigm shift in drug evaluation and holds promise to accelerate cures and meaningful treatments for Americans while reducing animal use," said FDA Commissioner Martin A. Makary, M.D., M.P.H. "By leveraging AI-based computational modeling, human organ model-based lab testing, and real-world human data, we can get safer treatments to patients faster and more reliably, while also reducing R&D costs and drug prices. It is a win-win for public health and ethics."

Key Benefits of Replacing Animal Testing in Monoclonal Antibody Safety Evaluation:

Advanced Computer Simulations: The roadmap encourages developers to leverage computer modeling and artificial intelligence to predict a drug's behavior. For example, software models could simulate how a monoclonal antibody distributes through the human body and reliably predict side effects based on this distribution as well as the drug's molecular composition. We believe this will drastically reduce the need for animal trials.

Human-Based Lab Models: The FDA will promote the use of lab-grown human "organoids" and organ-on-a-chip systems that mimic human organs – such as liver, heart, and immune organs – to test drug safety. These experiments can reveal toxic effects that could easily go undetected in animals, providing a more direct window into human responses.

Regulatory Incentives: The agency will work to update its guidelines to allow consideration of data from these new methods. Companies that submit strong safety data from non-animal tests may receive streamlined review, as the need for certain animal studies is eliminated, which would incentivize investment in modernized testing platforms.

Faster Drug Development: The use of these modern techniques should help speed up the drug development process, enabling monoclonal antibody therapies to reach patients more quickly without compromising safety.

Global Leadership in Regulatory Science: With this move, the FDA reaffirms its role as a global leader in modern regulatory science, setting new standards for the industry and encouraging the adoption of innovative, humane testing methods. In recent years, Congress and the scientific community have pressed for more human-relevant testing methods. Today's announcement is a step by the FDA towards its commitment to modernize regulatory science as technology advances.

Working in close partnership with federal agencies such as the National Institutes of Health, the National Toxicology Program and the Department of Veterans Affairs, the FDA aims to accelerate the validation and adoption of these innovative methods through the Interagency Coordinating Committee on the Validation of Alternative Methods (ICCVAM). The FDA and federal partners will host a public workshop later this year to discuss the roadmap and gather stakeholder input on its implementation. Over the coming year, the FDA aims to launch a pilot program allowing select monoclonal antibody developers to use a primarily non-animal-based testing strategy, under close FDA consultation. Findings from an accompanying pilot study will inform broader policy changes and guidance updates expected to roll out in phases.

Commissioner Makary noted the far-reaching significance of this proposal. "For patients, it means a more efficient pipeline for novel treatments. It also means an added margin of safety, since human-based test systems may better predict real-world outcomes. For animal welfare, it represents a major step toward ending the use of laboratory animals in drug testing. Thousands of animals, including dogs and primates, could eventually be spared each year as these new methods take root."

Related Information

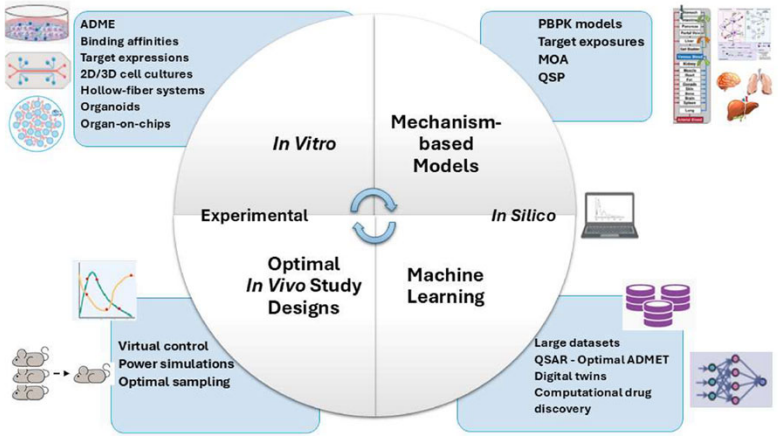
For more information on the FDA's NAMs roadmap and upcoming workshop

https://www.fda.gov/media/186092/download?attachment

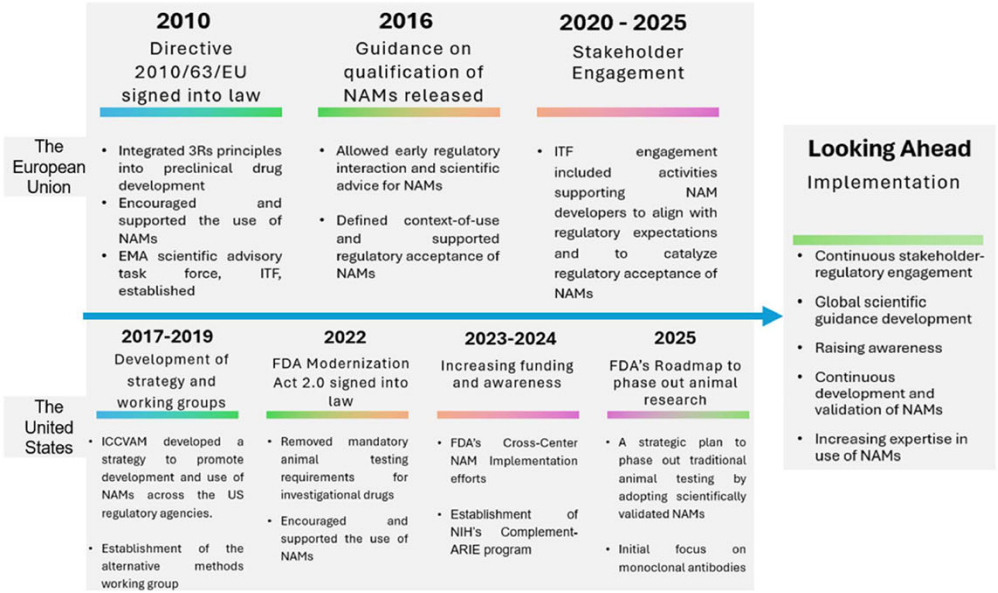
From Animals to Organoids

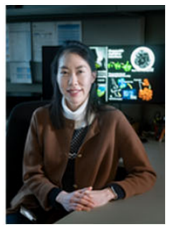
Human-relevant new approach methodologies

Human-relevant new approach methodologies (NAMs), including advanced in vitro systems, in silico mechanistic models, and computational techniques like artificial intelligence and machine learning, can improve translational success, as evident by several literature examples.

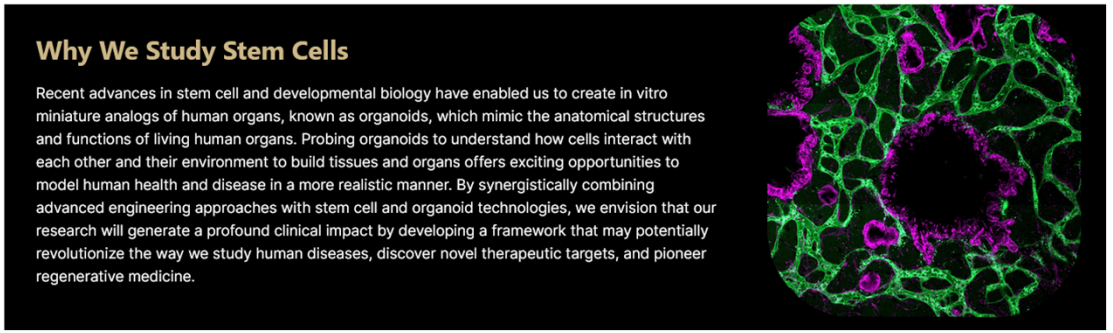


Mehta 2025, Modernizing preclinical drug development-The role of new approach methodologies

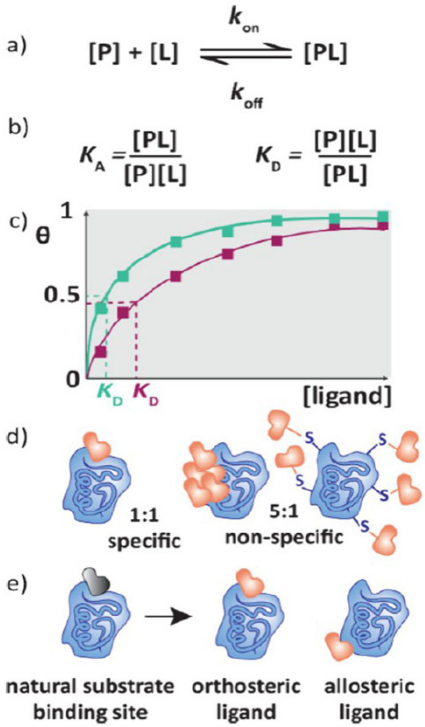




Professor Estelle Park (BME)



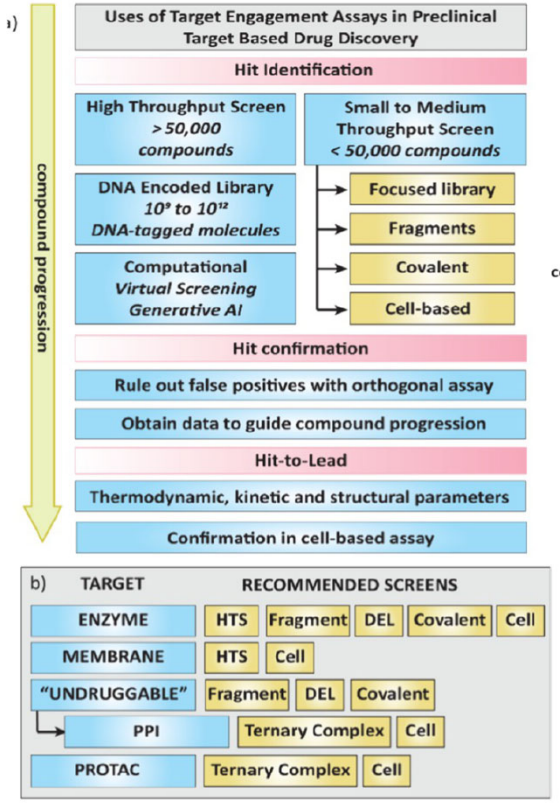
Target Engagement Assays in Early Drug Discovery



Orthosteric ligands bind to a protein's active site, directly blocking or activating its function, similar to how a natural substrate works, whereas allosteric ligands bind to a separate, distant site (known as an allosteric site) on the protein to induce a conformational change that indirectly alters the active site's activity or accessibility.

Allosteric modulation offers potential advantages in drug development, including increased selectivity and the ability to modulate protein function without competing directly with endogenous molecules.

Figure 1. Thermodynamic, kinetic and structural parameters of target engagement. a) Protein-ligand binding can be represented by a simple equilibrium, [P] = protein, [L] = ligand, [PL] = protein-ligand complex. The rate of complex formation is k_{on} and dissociation is k_{off}. b) Thermodynamic equilibrium constants K_A and K_D can be used to describe ligand binding. c) Titration of a ligand against a protein of interest enables identification of dissociation constants by finding the concentration where half of the binding sites are occupied. θ is the fraction bound of protein. The green line shows a stronger binding ligand with a lower K_D compared to the ligand shown in pink. d) Stoichiometry of the protein:ligand complex can give information about specificity of binding. e) Ligands can bind in orthosteric or allosteric sites.



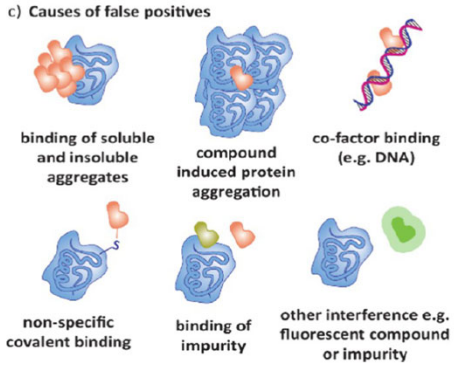
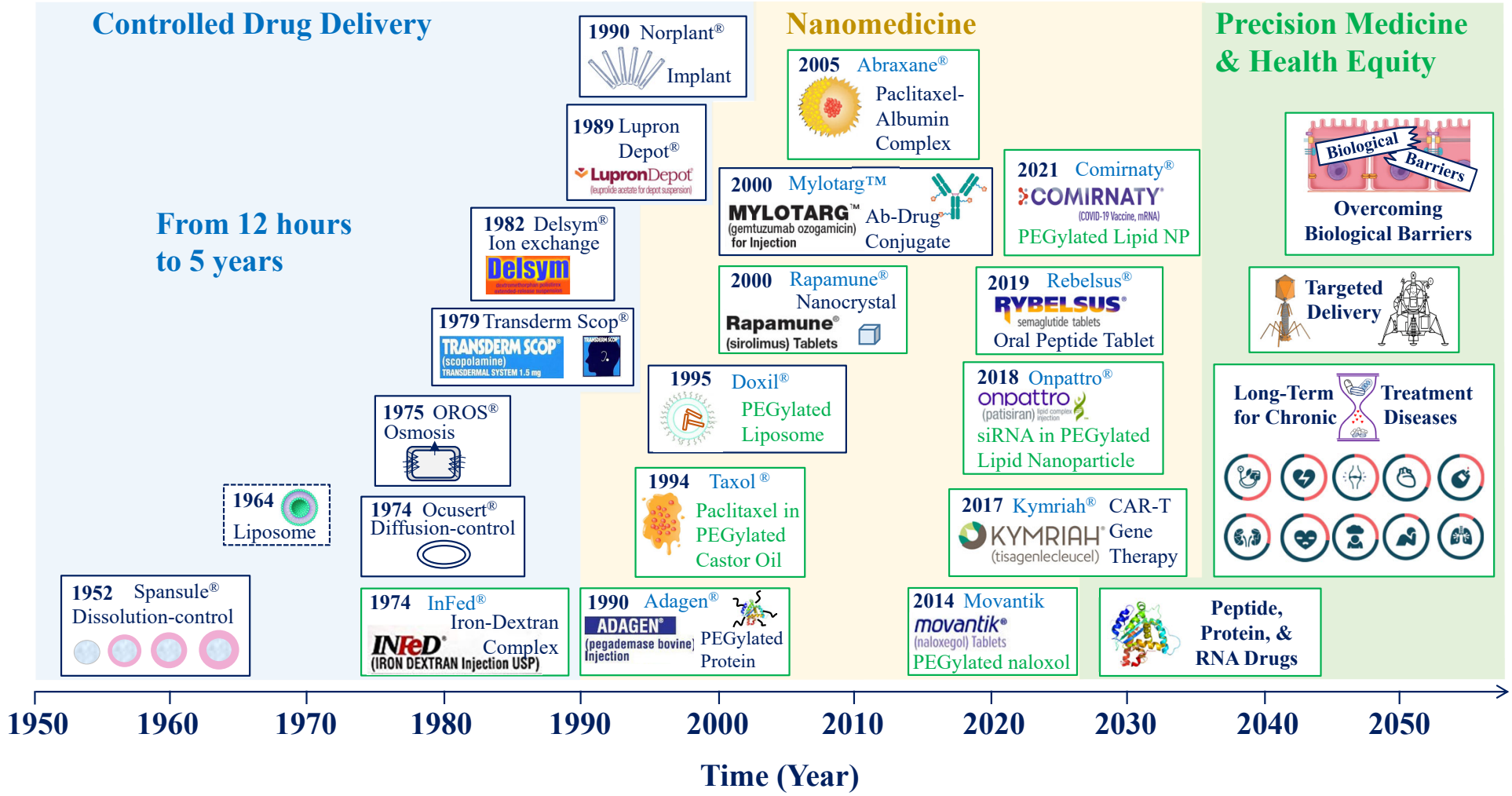


Figure 2. a) Target engagement assays can be used across different stages of the preclinical drug discovery timeline from hit identification with various screening strategies, to confirming hits from a primary screen as well as further characterization of compounds in the hit-to-lead stage. b) Selection of target engagement assay for screening can largely be guided by the class of target. Undruggable targets, which here we also include PPIs, often require different screening strategies than enzymes or membrane-bound proteins. c) False positives in target engagement assays can be caused by many factors.

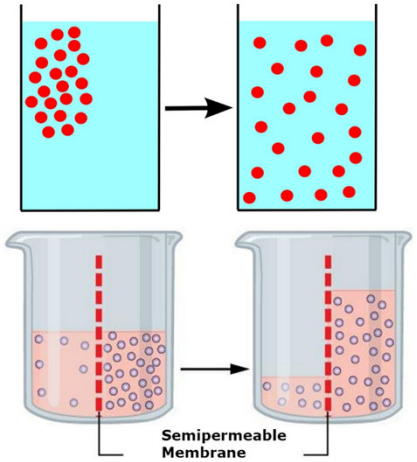
St John-Campbell 2025, Target engagement assays in early drug discovery

Controlled Drug Delivery Mechanisms

Evolution of Controlled Drug Delivery Systems



Diffusion



Diffusion

Movement of molecules from high concentration to low concentration in water (or in solvent).

Both solute and solvent move.

Osmosis

Movement of solvent (water) across a semipermeable membrane from high to low solvent concentration.

Only solvent move.

https://sciencenotes.org/osmosis-vs-diffusion-definition-and-examples/

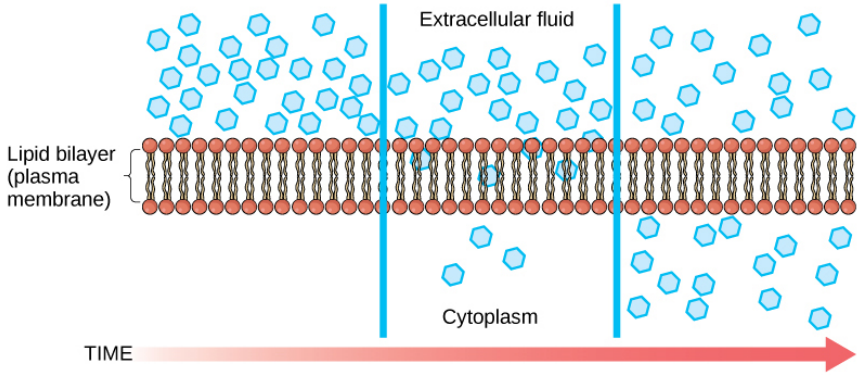
$$D = \frac{kT}{6\pi\eta r}$$

$$x = \sqrt{2Dt}\ cm^2/s$$

(One dimensional diffusion)

Permeation

Movement through a membrane depends on the properties of permeant and membrane.



https://openoregon.pressbooks.pub/mhccbiology101/chapter/diffusion/

Controlled Release Dosage Forms: Major Components

Drug + **Drug Delivery Module** + **Platform**

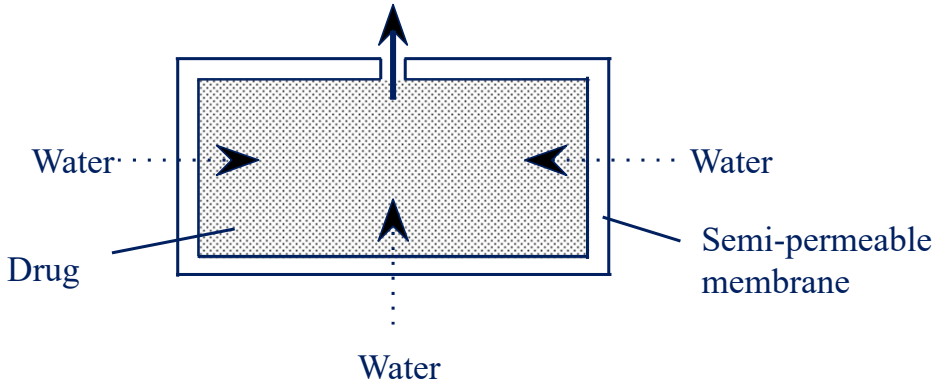
- Reservoir
- Delivery Portal (Exit)
- Energy Source
- Rate Controller

The drug component: The active pharmaceutical ingredient (API)

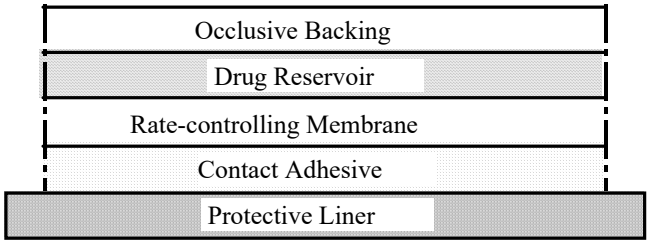
The platform is a distinct component from the drug component.

Some formulations combine the two distinct components that are physically or chemically combined into a single entity
→ Drug-device combination product.

Osmotic Tablet



Transdermal Patch



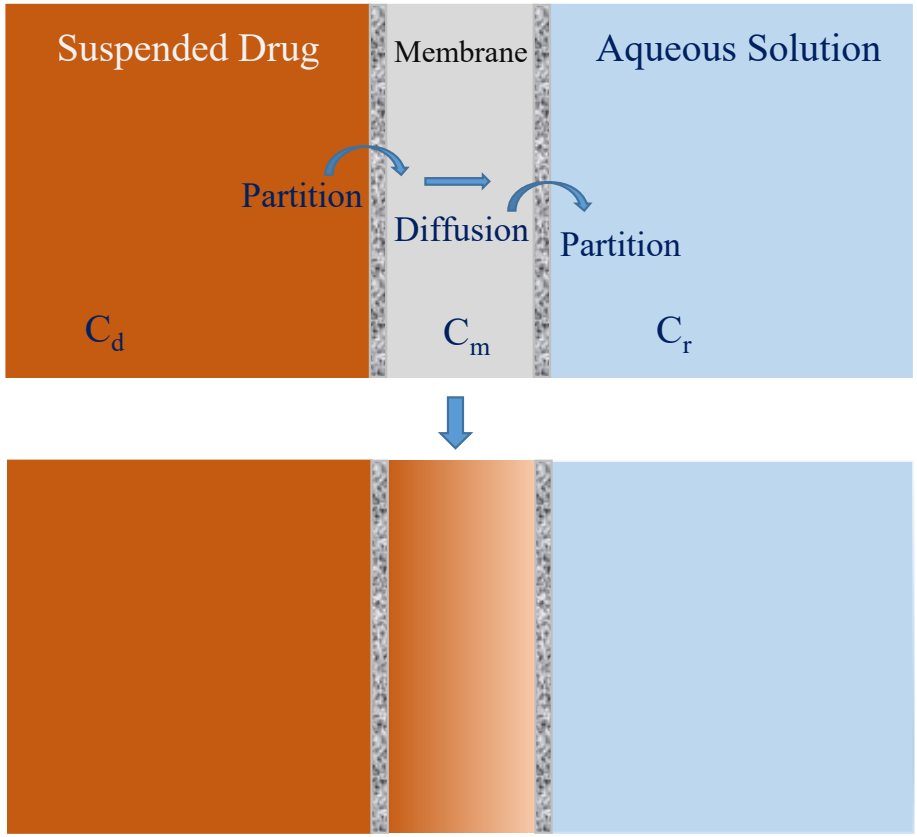
(not to scale)

Adhesive should not fail.
If the adhesive fails, the dosage form does not work.

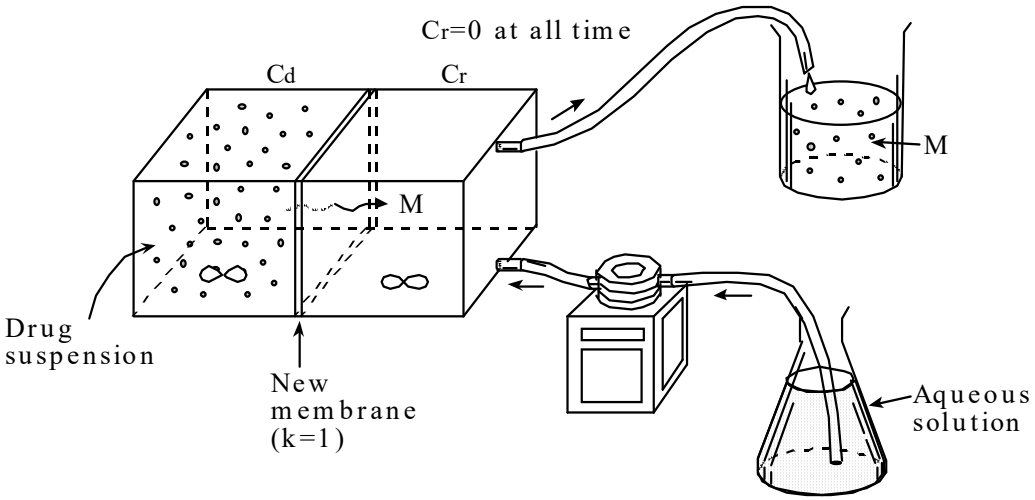
Drug Release through a Polymer Membrane (Solution-Diffusion Membrane)

A fresh nonporous, homogeneous polymer membrane.

Concentration on the donor side C_d remains constant.
The concentration on the receptor side C_r is zero at t = 0.



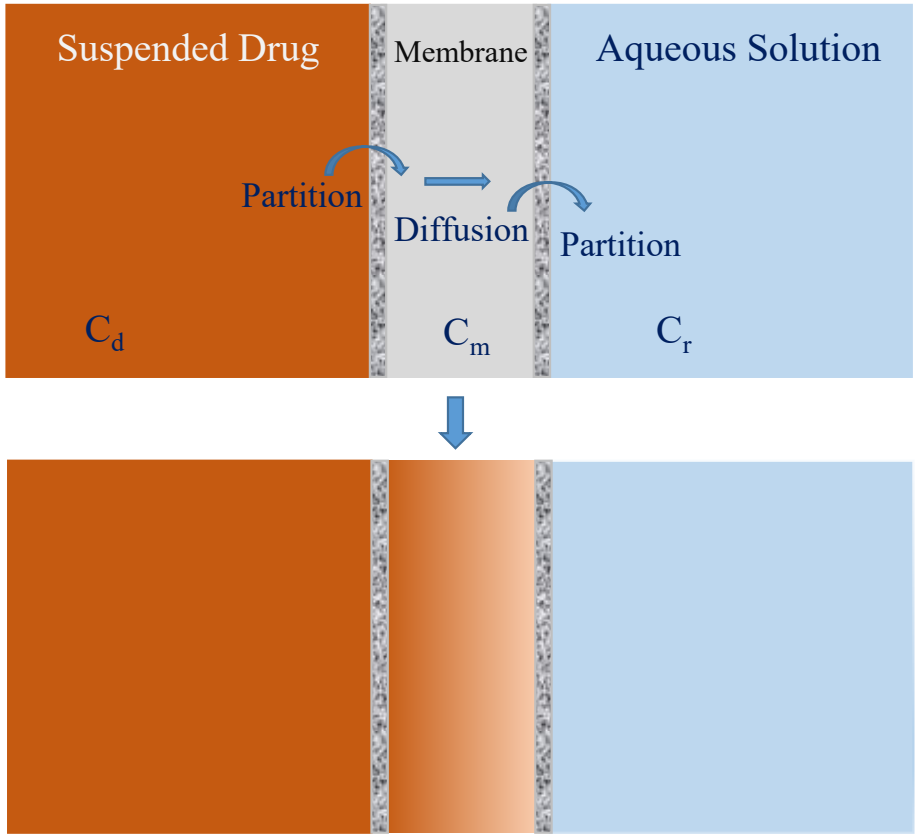
Lag time



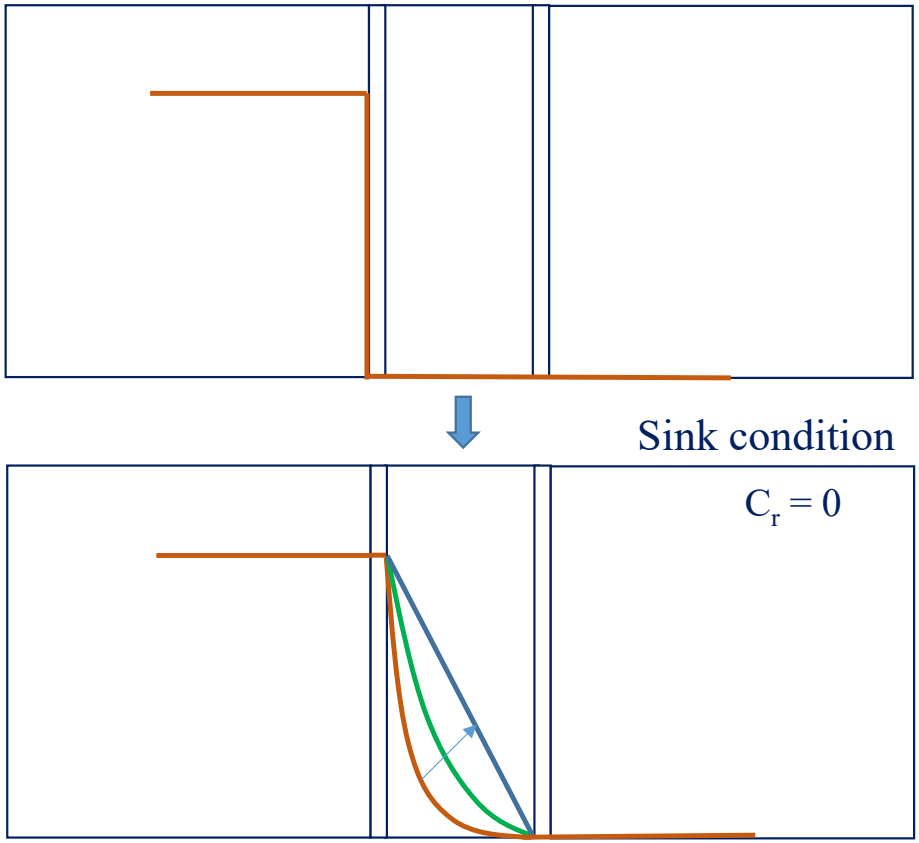
Drug Release through a Polymer Membrane (Solution-Diffusion Membrane)

A fresh nonporous, homogeneous polymer membrane.

Concentration on the donor side C_d remains constant.
The concentration on the receptor side C_r is zero at t = 0.



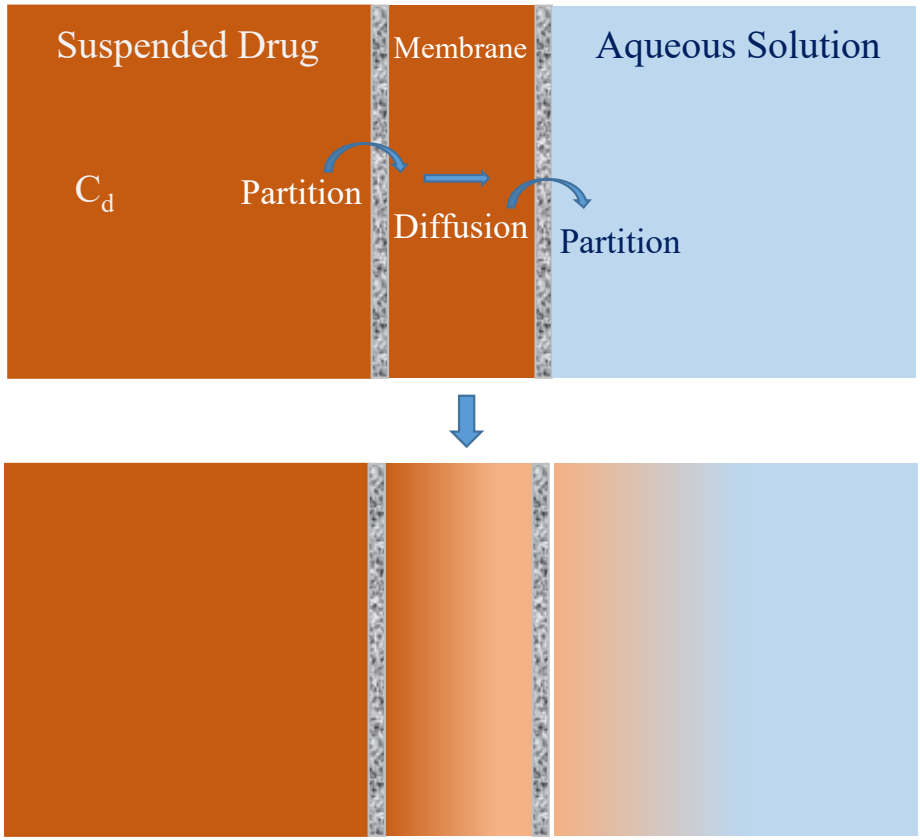
Lag time



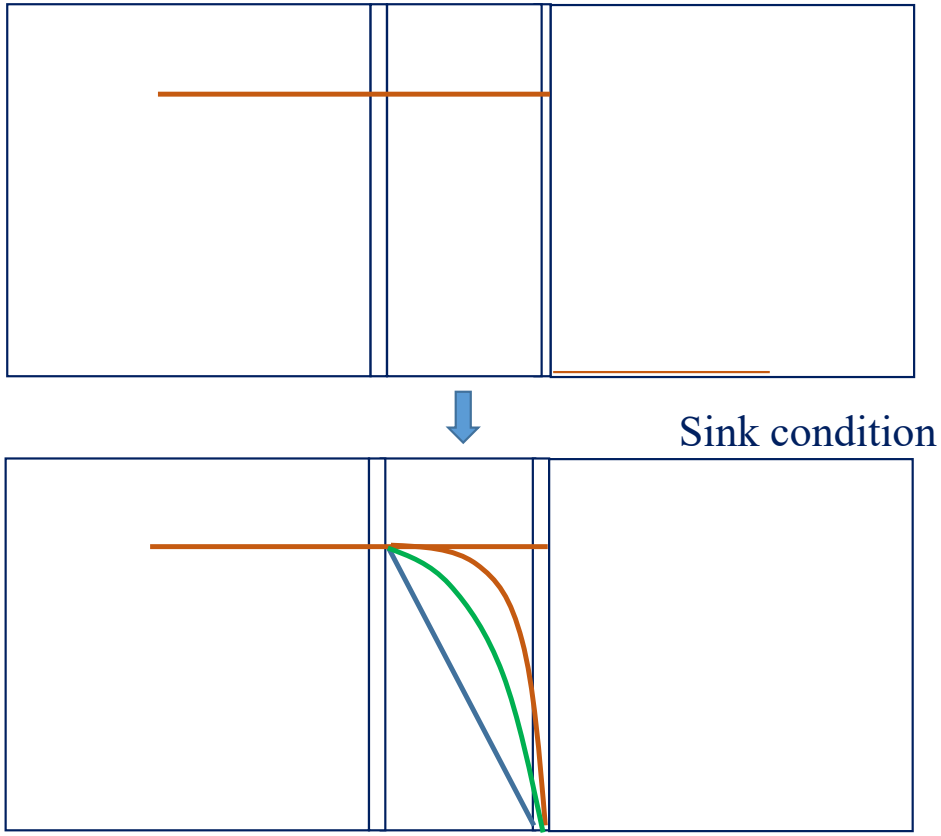
Lag time

Drug Release through a Polymer Membrane (Solution-Diffusion Membrane)

A nonporous, homogeneous polymer membrane presaturated with a drug



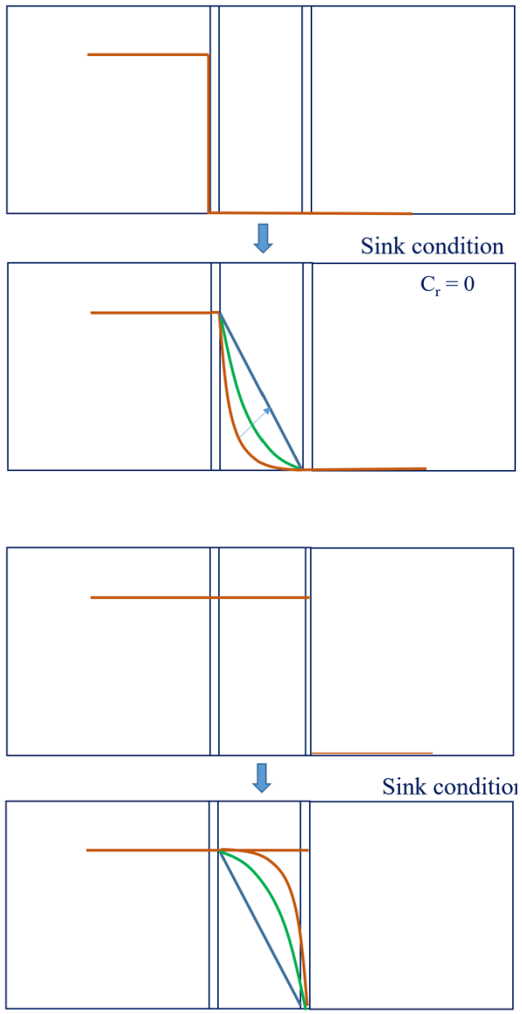
Burst effect



Sink condition

Lag time

Different Solubilities in Water and in Polymer



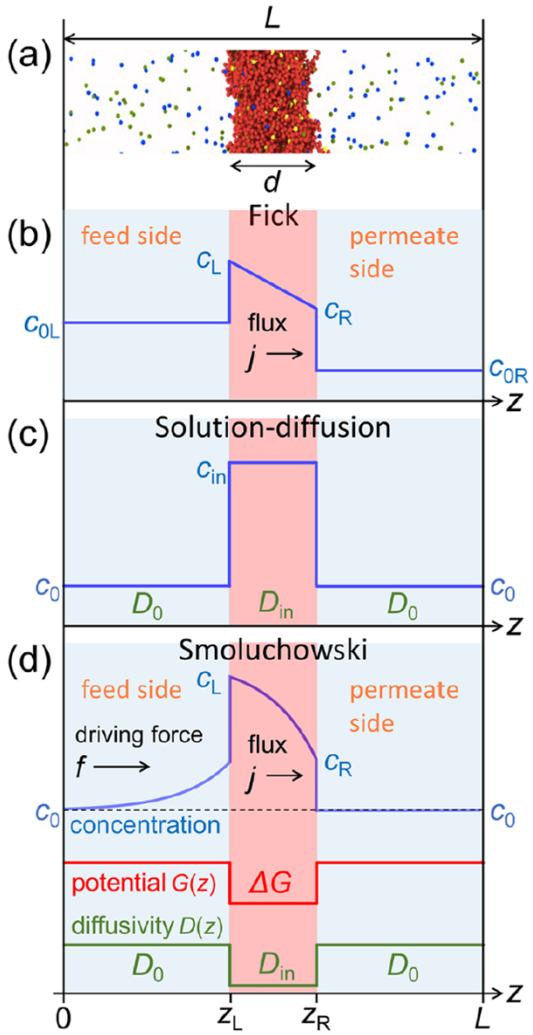
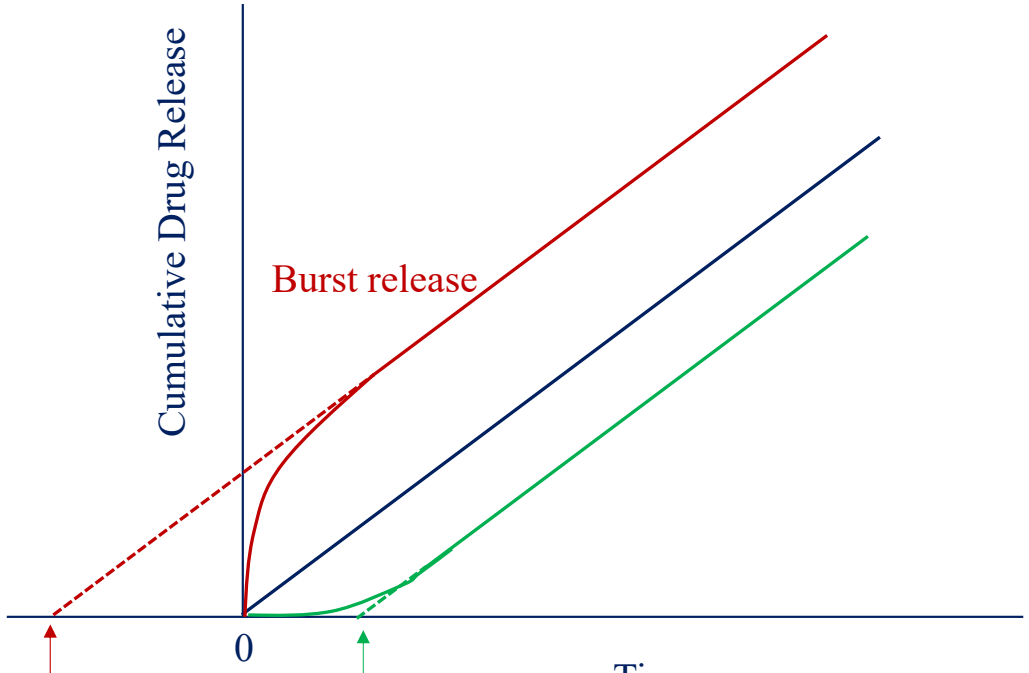


Figure 1. (a) Polymer network membrane (red) of thickness d, located at the center of a system of length L with penetrants (small blue and green spheres). (b–d) Various scenarios of membrane permeation in a continuum representation. (b) Fick's type of permeation: The penetrant flux j is generated by different bulk reservoir concentrations of penetrants c_{0L} (feed side) and c_{0R} (permeate side). (c) Solution–diffusion model with equilibrium penetrant concentrations c_0 in bulk and c_{in} inside the membrane and corresponding diffusion coefficients D_0 and D_{in}. (d) Smoluchowski-type permeation in nonequilibrium: The penetrant flux j is generated by a driving force f (any forces apart from the Fick type) acting on penetrants, which flows from the feed side to the permeate side. $G(z)$ and $D(z)$ are the position-dependent membrane potential and diffusivity, respectively (see eqs 15 and 16).

Kim 2022, Permeability of polymer membranes beyond linear response

Lag Time Release vs Burst Release

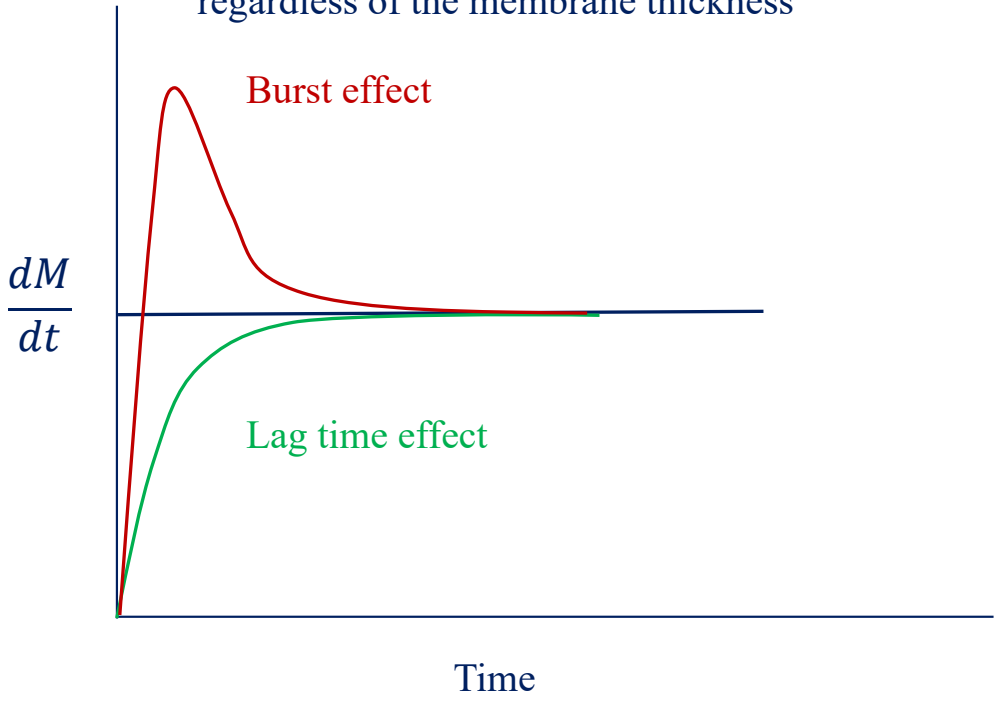
Slope = Steady-state release rate



$t_B = \frac{h^2}{3D}$

$t_L = \frac{h^2}{6D}$ (Lag time)

Once steady state has been achieved, zero-order release is observed regardless of the membrane thickness



$$M = S \cdot D \cdot K \frac{\Delta C}{h}\left(t + \frac{h^2}{3D}\right)$$

$$M = S \cdot D \cdot K \frac{\Delta C}{h}\left(t - \frac{h^2}{6D}\right)$$

Mechanisms of Controlled Drug Release

Physical Mechanisms

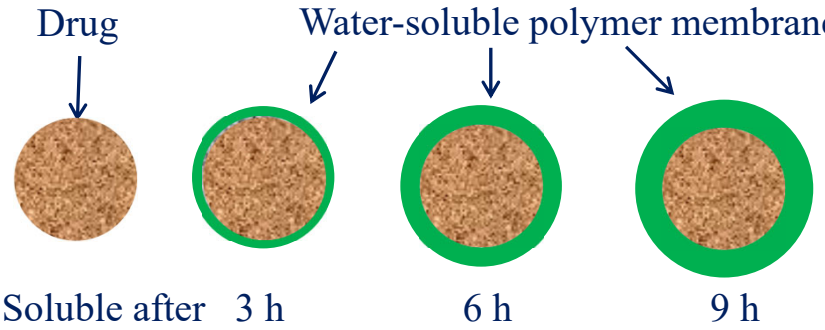
1. Dissolution
   - Reservoir System
   - Matrix System
2. Diffusion
   - Reservoir System (Reservoir = Encapsulated)
   - Monolithic System (Monolithic = Matrix)
     - Monolithic Solution System
     - Monolithic Dispersion System
3. Osmosis
4. Ion-Exchange

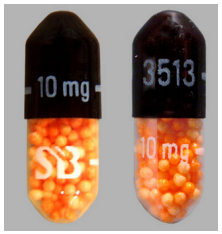
Chemical Mechanisms

5. Chemical Degradation
6. Enzymatic Degradation

Dissolution-Controlled System

Reservoir System (= Encapsulated Dissolution System)

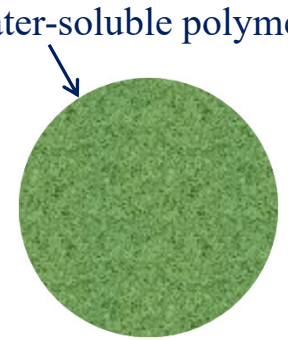




Spansule

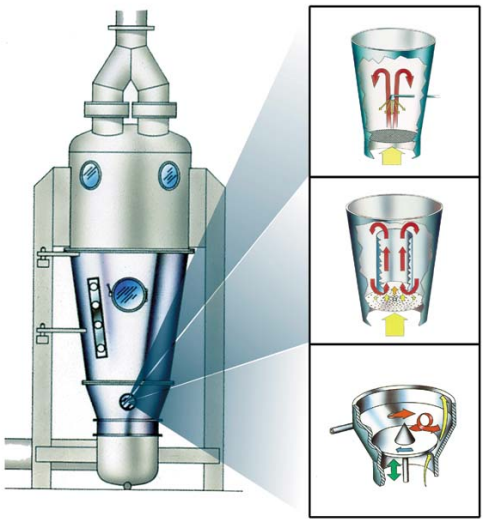
Dissolution of the polymeric material (e.g., PEG) is the key to this mechanism. All of the polymers used must be water soluble or degradable.

Matrix Dissolution System



The drug is homogeneously distributed throughout the polymer matrix.

As the polymer matrix dissolves, drug molecules are released.

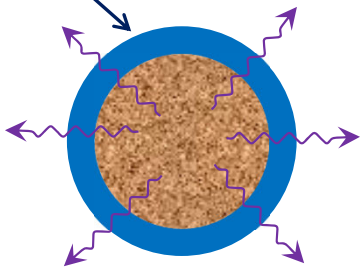


Fluid-Bed Wurster Coater

Diffusion-Controlled System

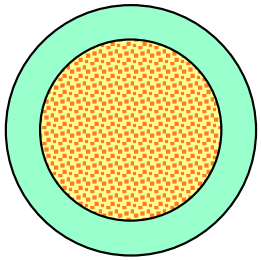
Reservoir System (= Encapsulated Diffusion System)

Water-insoluble polymer membrane

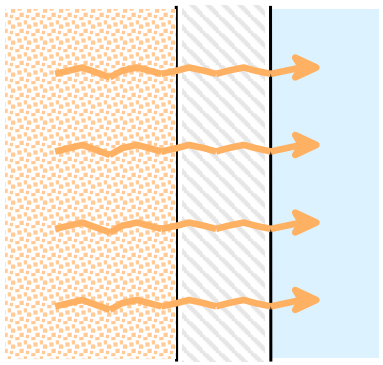


Dissolution of the polymeric material is the key to this mechanism. All of the polymers used must be water soluble or degradable.

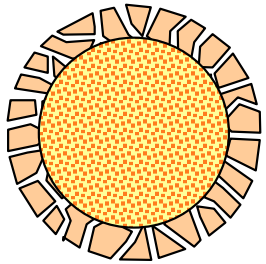
Nonporous membrane



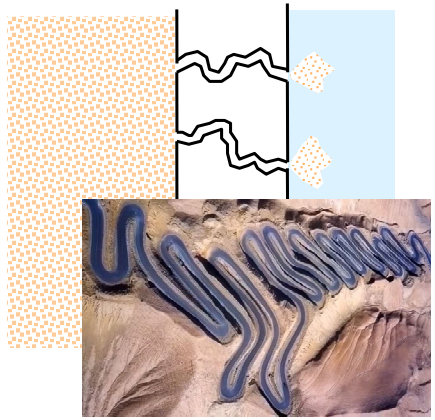
Drug must diffuse through solution-diffusion membrane



Microporous membrane

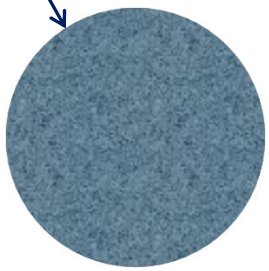


Drug is released through micropores (usually filled with water or oil)



Monolithic Diffusion System

Water-insoluble polymer matrix

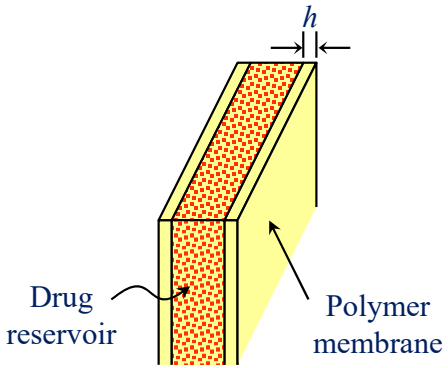


The drug is homogeneously distributed throughout the polymer matrix.

As the polymer matrix dissolves, drug molecules are released.

Diffusion-Controlled System

1-Dimension Reservoir Device (Slab)

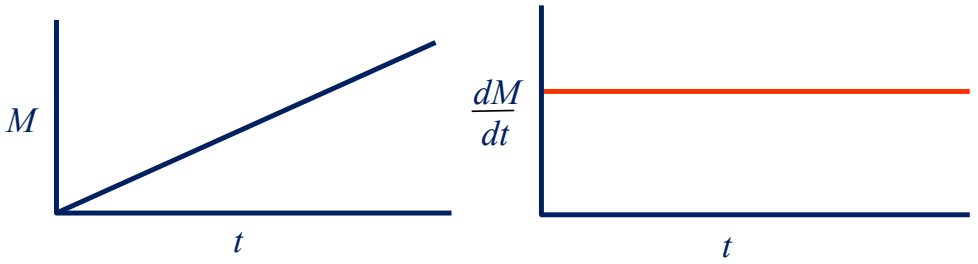


$$M = \frac{S \cdot D \cdot K \cdot \Delta C \cdot t}{h}$$

$$\frac{dM}{dt} = \frac{S \cdot D \cdot K \cdot \Delta C}{h}$$

$$\Delta C = C_s - C$$

K = partition coefficient



Drug release is zero order.

Norplant® Subdermal Implant

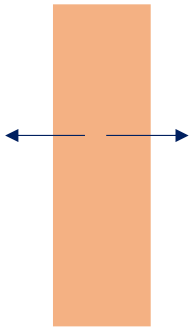
Six matchstick-size silicon rubber rods inserted into the upper arm. Each rod contains 36 mg levonogestrel.
The system releases 85 mg/d initially, which declines to 30 mg/d during its useful life (up to 7 years).

Microporous polypropylene film (Celgard®) in disposable butane lighters

Maintain constant flow and flame height, regardless of ambient pressure and fuel level.

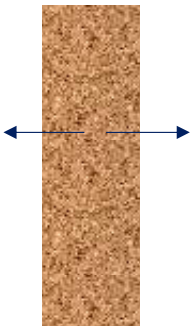
Diffusion-Controlled Monolithic System

Monolithic Solution System



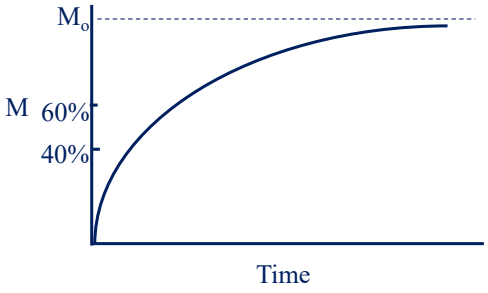
C_{max} is the drug solubility in solution.

Monolithic Dispersion System



C_{max} depends on the solid drug content.

C_{max}: The maximum drug concentration



Decrease in release rate due to increase in diffusion path length

$$\frac{dM}{dt} = \frac{S \cdot D \cdot K \cdot \Delta C}{h}$$

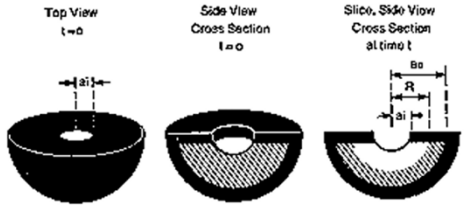


FIGURE 5. Diagram of an inwardly-releasing hemisphere; a, is the inner radius, a, is the outer radius, and R is the distance to the interface between the dissolved region (white area) and the dispersed zone (diagonal lines). Black represents laminated regions through which release cannot occur. (From Hsieh, D. S. T. et al., *J. Pharm. Sci.*, 72, 17, 1983. With permission.)

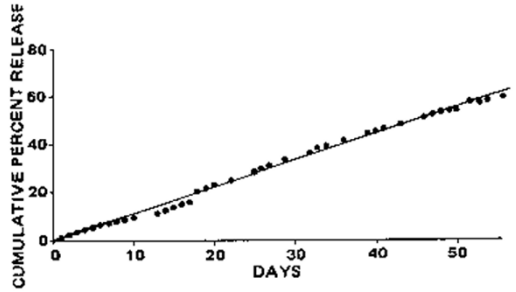


FIGURE 6. Cumulative release of bovine serum albumin vs. time. The matrix was made of ethylene-vinyl acetate copolymer and bovine serum albumin. Standard error of the mean of the cumulative release at each time point was within 12%. (From Hsieh, D. S. T. et al., *J. Pharm. Sci.*, 72, 17, 1983. With permission.)

Japanese Beetle Lure & Trap

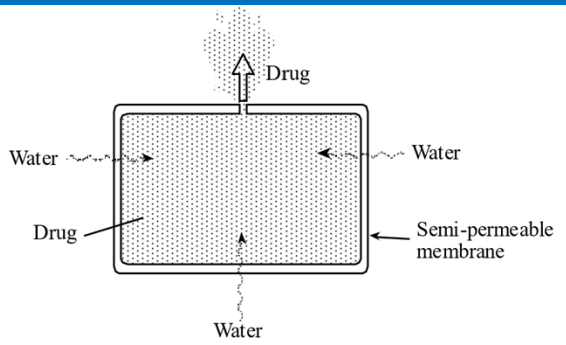
- Lures beetles with pheromones
- No sprays required
- Replace lures every 4-6 weeks

Attracts adult using an irresistible pheromone and floral lure. Set out in mid-June, 50 ft. upwind of vulnerable plants. Includes trap assembly, large-capacity bag and lures. Japanese Beetle Trap lures should be replaced every four to six weeks.

Japanese beetles are metallic green and copper-colored, and usually grow to about 1/2" long. They will eat almost any plant, but especially love beans and corn. This beetle's larvae are rarely noticed, but their diet of grass and vegetable roots can reduce crop yields and weaken lawns.

https://www.gurneys.com/product/japanese-beetle-trap

Osmosis-Controlled System



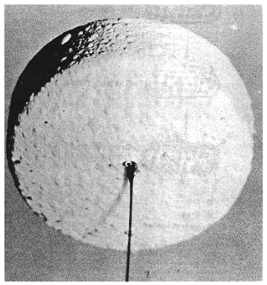
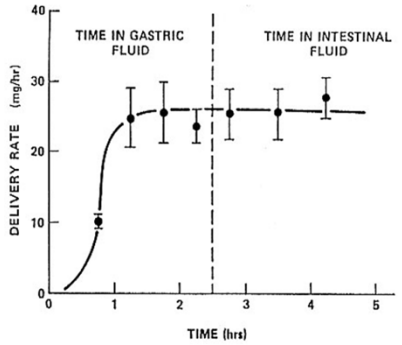
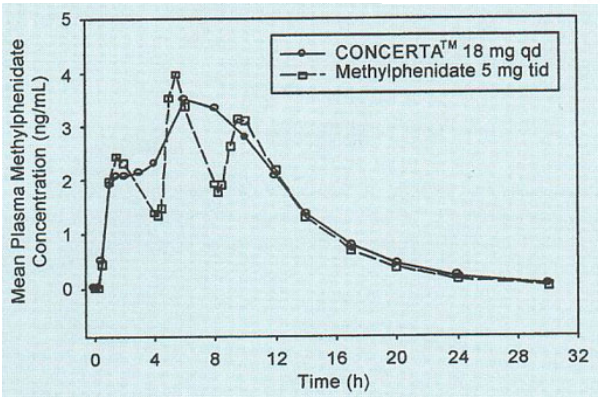


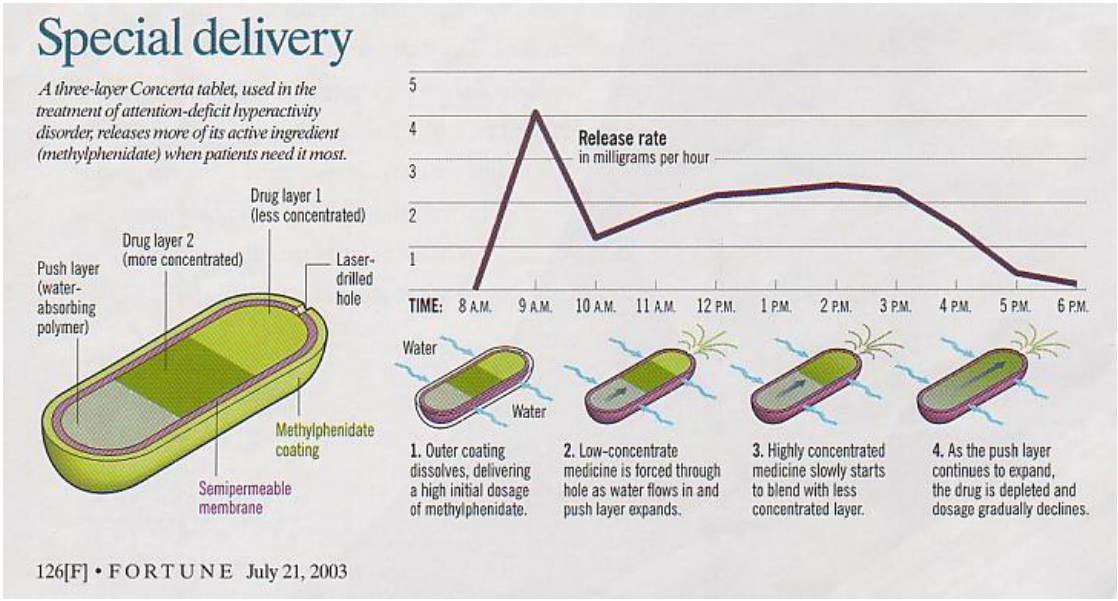
FIGURE 13. Demonstration model of an Oros® tablet (courtesy of Merck Sharp & Dohme, The Netherlands).

Typical in vitro release rate of an OROS® tablet

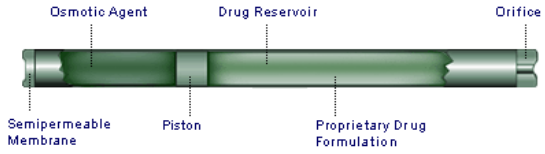


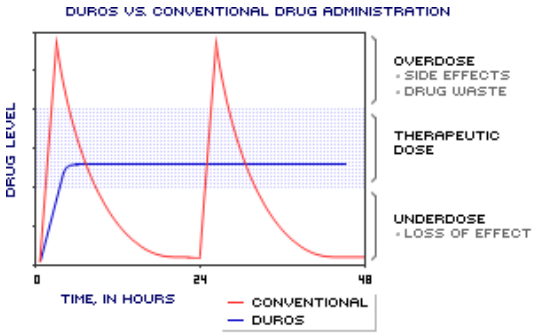


Mean plasma methylphenidate concentrations with Concerta and Immediate-release tablet.



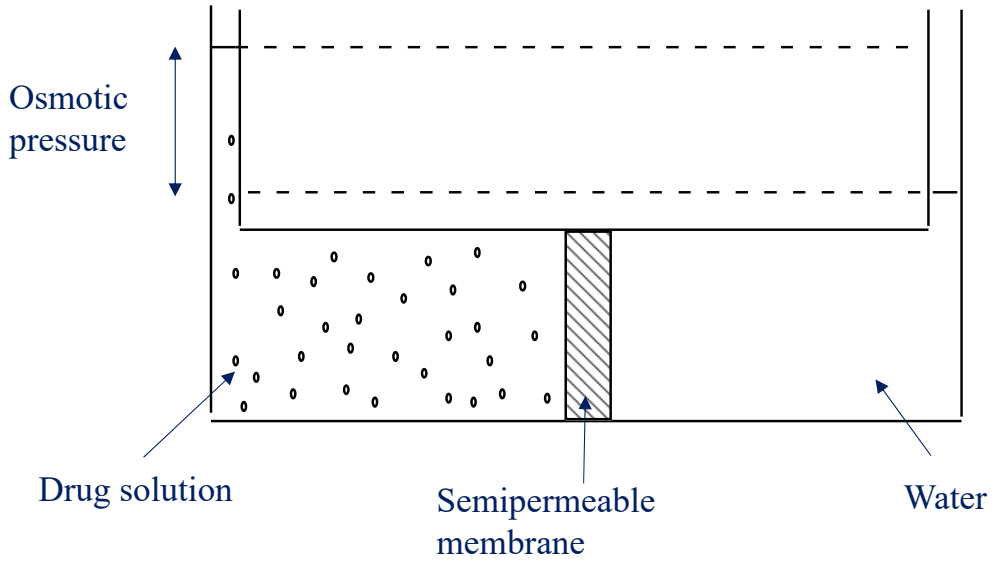
DUROS® implant technology DURECT



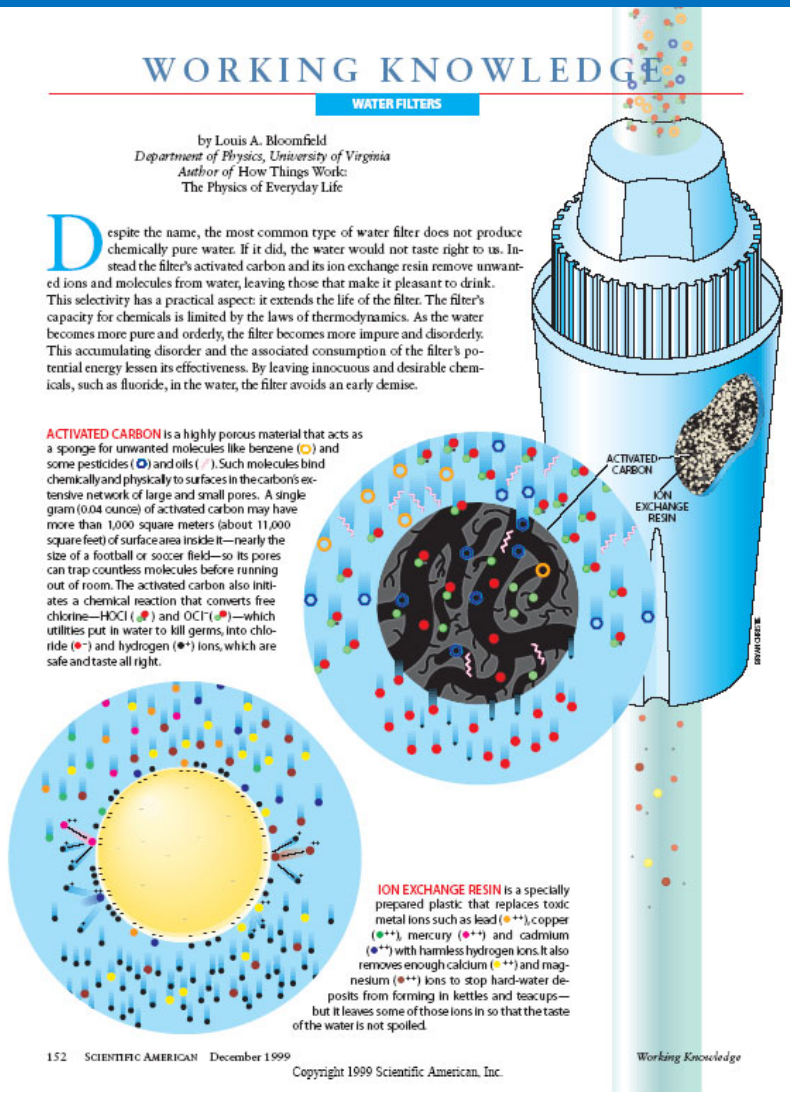


Reverse Osmosis

Seawater undergoes reverse osmosis, in which high pressure forces the water through membranes that remove impurities.



Ion Exchange-controlled Drug Release



WORKING KNOWLEDGE

WATER FILTERS

by Louis A. Bloomfield
Department of Physics, University of Virginia
Author of How Things Work:
The Physics of Everyday Life

Despite the name, the most common type of water filter does not produce chemically pure water. If it did, the water would not taste right to us. Instead the filter's activated carbon and its ion exchange resin remove unwanted ions and molecules from water, leaving those that make it pleasant to drink. This selectivity has a practical aspect: it extends the life of the filter. The filter's capacity for chemicals is limited by the laws of thermodynamics. As the water becomes more pure and orderly, the filter becomes more impure and disorderly. This accumulating disorder and the associated consumption of the filter's potential energy lessen its effectiveness. By leaving innocuous and desirable chemicals, such as fluoride, in the water, the filter avoids an early demise.

ACTIVATED CARBON is a highly porous material that acts as a sponge for unwanted molecules like benzene (○) and some pesticides (●) and oils (/). Such molecules bind chemically and physically to surfaces in the carbon's extensive network of large and small pores. A single gram (0.04 ounce) of activated carbon may have more than 1,000 square meters (about 11,000 square feet) of surface area inside it—nearly the size of a football or soccer field—so its pores can trap countless molecules before running out of room. The activated carbon also initiates a chemical reaction that converts free chlorine—HOCl (●) and OCl^- (●)—which utilities put in water to kill germs, into chloride (●⁻) and hydrogen (●⁺) ions, which are safe and taste all right.

ACTIVATED CARBON

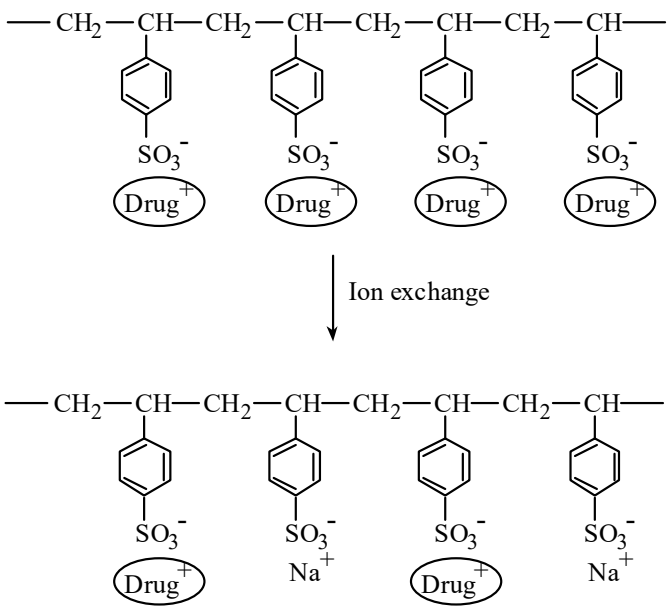
ION EXCHANGE RESIN

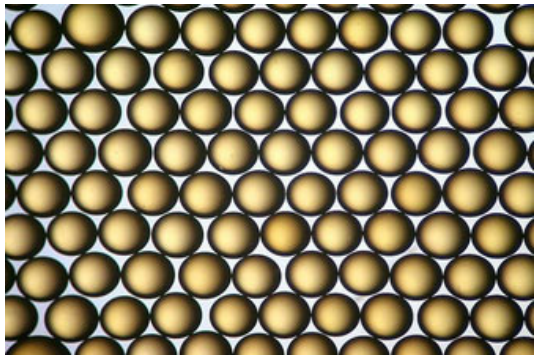
ION EXCHANGE RESIN is a specially prepared plastic that replaces toxic metal ions such as lead (●⁺⁺), copper (●⁺⁺), mercury (●⁺⁺) and cadmium (●⁺⁺) with harmless hydrogen ions. It also removes enough calcium (●⁺⁺) and magnesium (●⁺⁺) ions to stop hard-water deposits from forming in kettles and teacups—but it leaves some of those ions in so that the taste of the water is not spoiled.

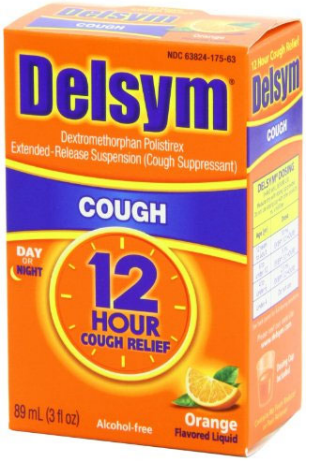
152 SCIENTIFIC AMERICAN December 1999

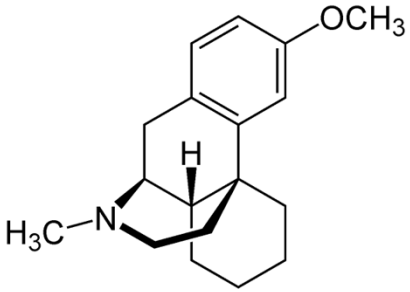
Copyright 1999 Scientific American, Inc.

Working Knowledge









Dextromethorphan

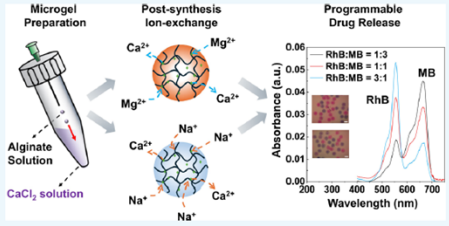
Ion Exchange-controlled Drug Release

Programmable Cargo Release from Jet-Printed Microgel Particles via an In Situ Ionic Exchange Method

Rong Ma,[¶] Jihpeng Sun,[¶] Sungwan Park, Fiona Nikolla, and Albert Tianxiang Liu*

Cite This: https://doi.org/10.1021/cbe.5c00017 Read Online

ACCESS | Metrics & More | Article Recommendations | Supporting Information



ABSTRACT: Hydrogel-based drug delivery systems hold significant clinical potential by enabling precise spatial and temporal control over therapeutic release, ranging from metabolites, macromolecules to other cellular and subcellular constructs. However, achieving programmable release of payloads with diverse molecular weights at distinct rates typically requires complex polymer designs that can compromise the accessibility and biocompatibility of the delivery system. We present a scalable method for producing injectable, micrometer-scale alginate hydrogel particles (microgels) with precisely tuned microstructures for multiplexed, programmable cargo release. Our approach integrates an established jetting technique with a simple postsynthesis ion-exchange process to fine-tune the cross-linked microstructure of alginate microgels. By varying cation type (Ca^{2+}, Mg^{2+}, Na^{+}) and concentration, we systematically modulate the microgels' chemical and physical properties to control release rates of model compounds, including rhodamine B, methylene blue, and dextrans of various molecular weights. Additionally, a PEG-alginate composite microgel system is used to demonstrate the pre-programmed stepwise release of rhodamine B. These findings offer a straightforward strategy for postsynthetic manipulation of ionic microgels with controllable release performances, paving the way for advanced biomedical applications.

KEYWORDS: *microgels, jet printing, ion exchange, programmable release, release kinetics*

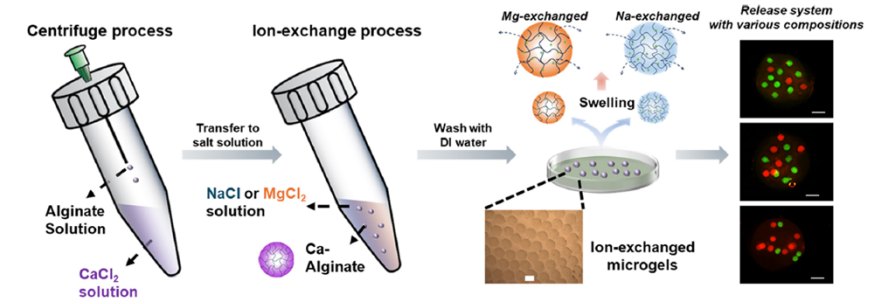
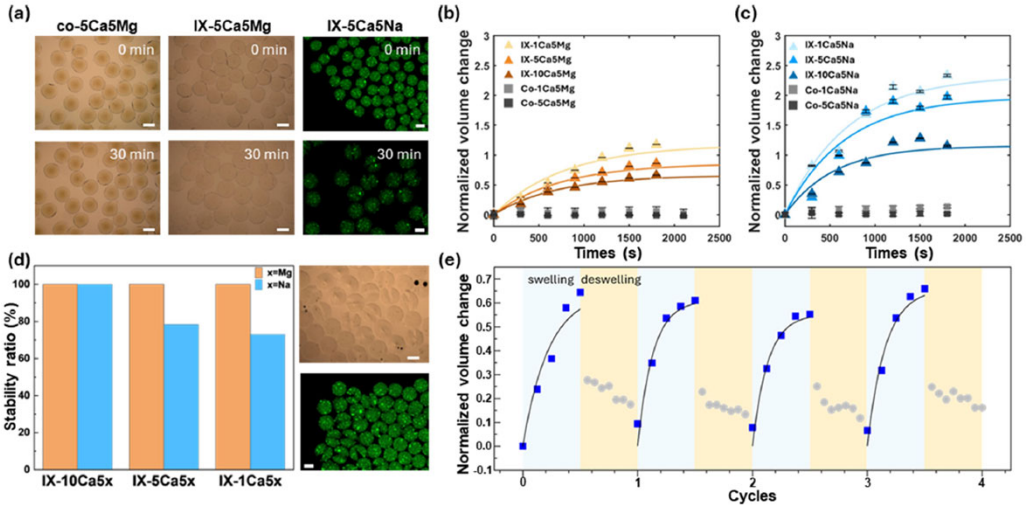


Figure 1. Schematic illustration of the experimental workflow established in this study, including centrifugal-force-driven alginate microgel synthesis, followed by ion-exchange (IX), and subsequent microgel swelling and cargo release. Inset (middle-bottom panel): optical micrograph of as-prepared alginate microgels post IX. Scale bar: 500 μm. Inset (right panels): fluorescent micrographs of a complex delivery system composed of various number ratios of post-IX microgels containing different dye-labeled dextrans (green and red) for multiplexed cargo release. Scale bars: 1000 μm.



Ma 2025, Programmable cargo release from jet-printed microgel particles via an in situ ionic exchange method

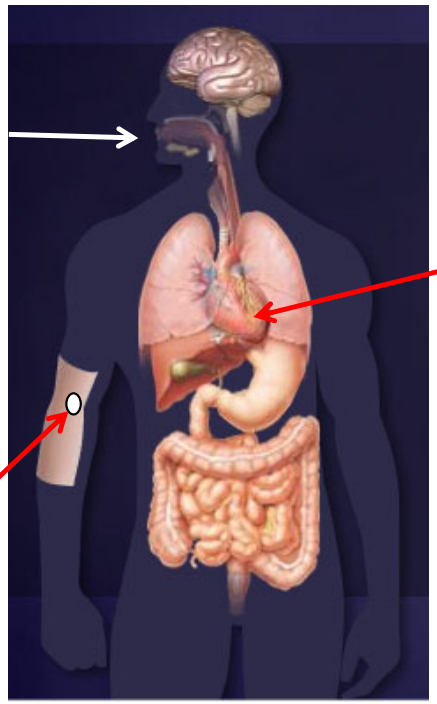
Evolution of Drug Delivery Systems

Drug Delivery Routes

Oral Delivery:
<1 min ~ > 1 day

Transdermal:
1 day ~ 1 week

I.V. Infusion
~ 1 day

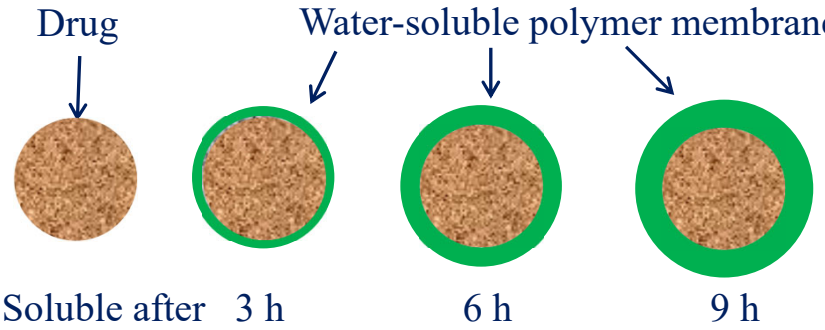


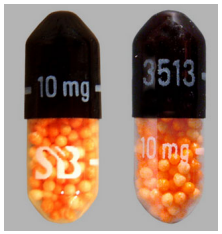
Localized Delivery:
1 month ~ 1 year

Long-acting Injectables:
1 month ~ 6 months

Dissolution-Controlled System

Reservoir System (= Encapsulated Dissolution System)

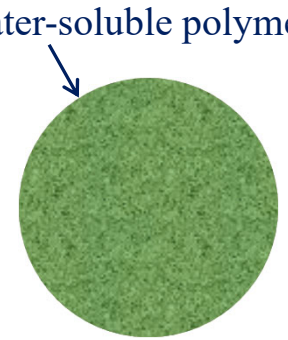




Spansule

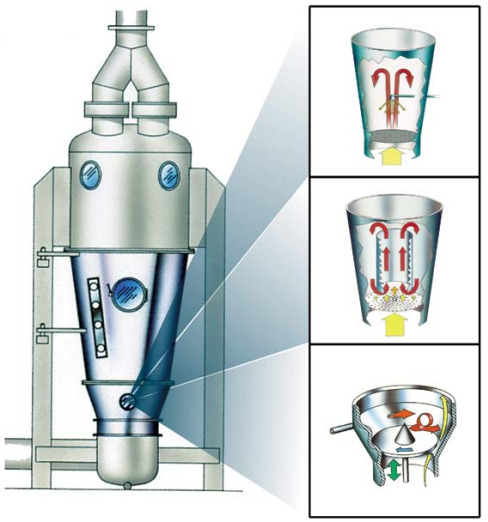
Dissolution of the polymeric material (e.g., PEG) is the key to this mechanism. All of the polymers used must be water soluble or degradable.

Matrix Dissolution System



The drug is homogeneously distributed throughout the polymer matrix.

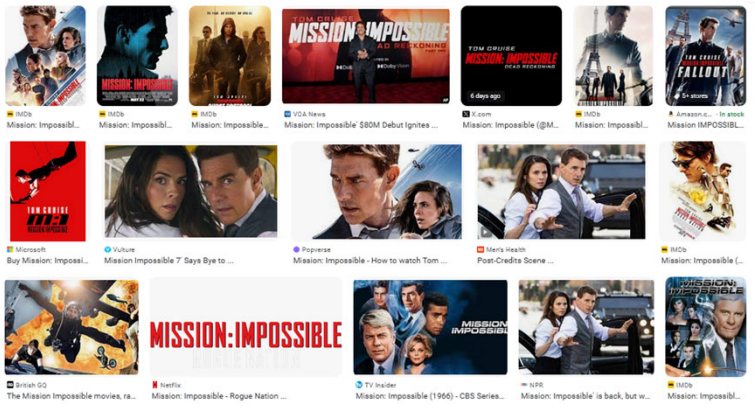
As the polymer matrix dissolves, drug molecules are released.



Fluid-Bed Wurster Coater

Columbo: Uneasy Lies the Crown (1990)

Mission: Impossible (1966)

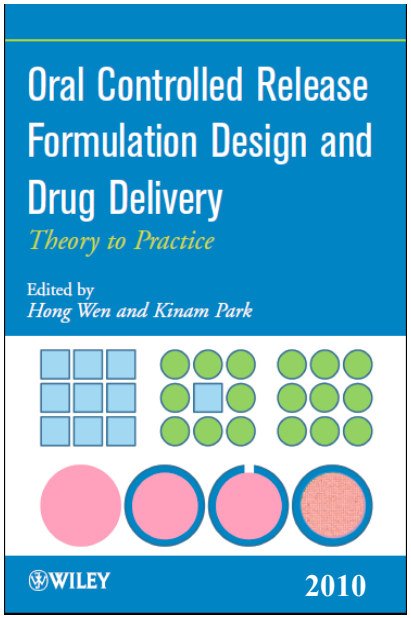


Good morning, Mr. Phelps. ---. Your mission, Jim, should you choose to accept it, is to ---. As always, should you or any of member of your team be caught or killed, the Secretary will disavow any knowledge of your actions. This tape will self-destruct in five seconds. Good luck to you, Jim.

Oral Controlled Drug Delivery Systems

Highly Successful Oral Sustained Release Formulations

12-hour delivery, 24-hour delivery



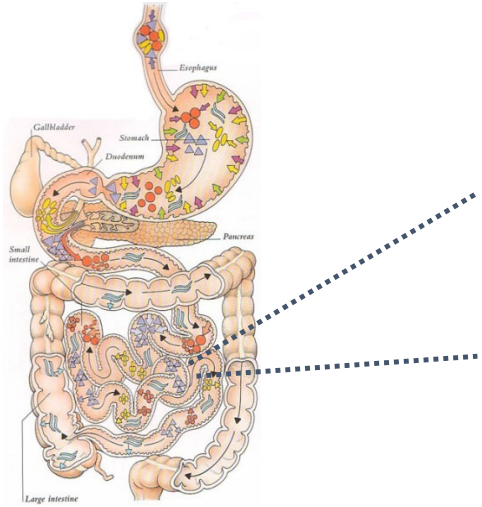
Ahmed & Naini: Generic oral controlled release product development: Formulation and process considerations. Ch. 19.

Sklar SH. Extended-release drug patents: can they save big pharma's blockbuster medicines from the generic scrap heap?. *Pharm. Law Ind. Rep.* 2006;4(6):1–8.

TABLE 19.1 Examples of Branded Extended Release Products with Associated Patent Claims

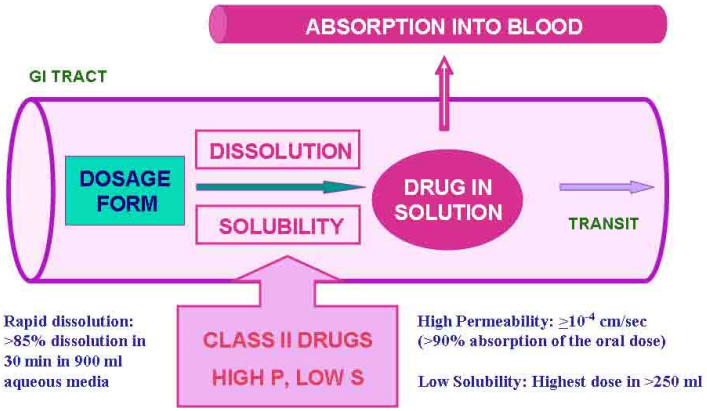
Brand Product	Generic Name	Patent(s)	Claim Types
Adderall XR®	Amphetamine salts	US 6,322,819	FPK
		US 6,605300	FPK
Biaxin® XL	Clarithromycin	US 6,010,718	FPK
		US 6,551,616	F
		US 6,872,407	PK
Concerta®	Methylphenidate	US 6,919,373	PK
		US 6,930,129	PK
Depakote® ER	Divalproex	US 6,419,953	F
		US 6,511,678	FPK
		US 6,528,090	FPK
Ditropan® XL	Oxybutynin	US 6,124,355	PK
Effexor® XR	Venlafexine	US 6,274,171	F, FPK
		US 6,403,120	PK, FPK
		US 6,419,958	PK
Glucophage® XR	Metformin	US 6,475,521	F, FPK
Niaspan®	Niacin	US 6,406,715	PK
		US 6,676,967	PK
Toprol® XL	Metoprolol	US 5,001,161	F
Wellbutrin® XL	Bupropion	US 6,096,341	FPK

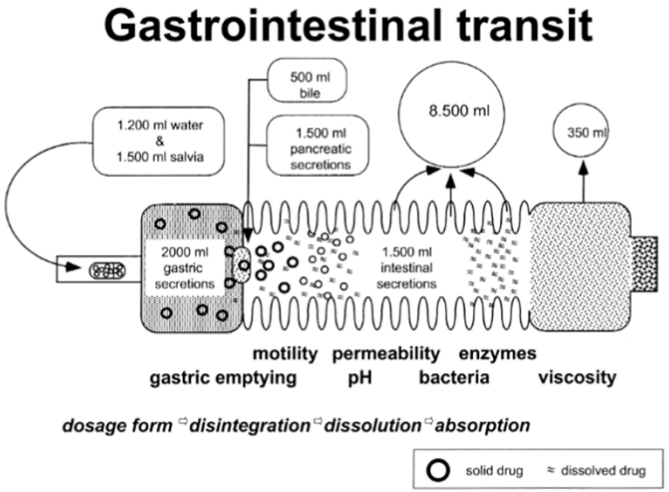
Need for Formulations of Poorly-Soluble Drugs



Increased absorption of poorly water-soluble drugs

Drug absorption from the GI tract





Lobenberg 2000, Modern bioavailability, bioequivalence and biopharmaceutics classification system

Biopharmaceutics Classification System

Table I
BCS classification of drugs and in vitro/in vivo correlation expectations for immediate release products based on the biopharmaceutics class[a]

Class	Solubility	Permeability	IVIVC expectation
I	High	High	IVIVC if the dissolution rate is slower than the gastric emptying rate, otherwise limited or no correlation
	(5~10%) →35%		
II	Low	High	IVIVC expected if the in vitro dissolution rate is similar to the in vivo dissolution rate, unless the dose is very high
	(60~70%)→30%		
III	High	Low	Absorption (permeability) is rate determining and limited or no IVIVC with dissolution rate
	(5~10%) →25%		
IV	Low	Low	Limited or no IVIVC expected
	(10~20%) →10%		

THE BIOPHARMACEUTICS CLASSIFICATION SYSTEM

A. Solubility

The **solubility** class boundary is based on the highest strength of an IR product that is the subject of a biowaiver request. A drug substance is considered highly soluble when the highest strength is soluble in 250 mL or less of aqueous media within the pH range of 1 - 6.8 at 37 ± 1°C. The volume estimate of 250 mL is derived from typical BE study protocols that prescribe administration of a drug product to fasting human volunteers with an 8 fluid ounce glass of water.

B. Permeability

The **permeability** class boundary is based indirectly on the extent of absorption (fraction of dose absorbed, not systemic BA) of a drug substance in humans, and directly on measurements of the rate of mass transfer across human intestinal membrane. Alternatively, other systems capable of predicting the extent of drug absorption in humans can be used (e.g., in situ animal, in vitro epithelial cell culture methods). A drug substance is considered to be highly permeable when the systemic BA or the extent of absorption in humans is determined to be 85 percent or more of an administered dose based on a mass balance determination (along with evidence showing stability of the drug in the GI tract) or in comparison to an intravenous reference dose.

C. Dissolution

An IR drug product is considered rapidly dissolving when a mean of 85 percent or more of the labeled amount of the drug substance dissolves within 30 minutes, using United States Pharmacopeia (USP) Apparatus 1 at 100 rpm or Apparatus 2 at 50 rpm (or at 75 rpm when appropriately justified (see section III.C.) in a volume of 500 mL or less (or 900 mL when appropriately justified) in each of the following media: (1) 0.1 N HCl or Simulated Gastric Fluid USP without enzymes; (2) a pH 4.5 buffer; and (3) a pH 6.8 buffer or Simulated Intestinal Fluid USP without enzymes.

An IR product is considered very rapidly dissolving when a mean of 85 percent or more of the labeled amount of the drug substance dissolves within 15 minutes, using the above mentioned conditions.

The BCS is used to set drug product dissolution standards to reduce the in vivo bioequivalence (BE) requirements.

(G.L. Amidon, H. Lennernas, V.P. Shah, J.R. Crison, A theoretical basis for a biopharmaceutic drug classification: the correlation of in vitro drug product dissolution and in vivo bioavailability, Pharm. Res. 12 (1995) 413-420).

Biopharmaceutics Classification System (BCS)

An inhalation-based biopharmaceutics classification system (iBCS).

To describe the propensity for dissolution rate-limited uptake of the deposited dose in an iBCS, we use the same relationship for the dose number (D_o) as used by the giBCS, but instead of the nominal dose, the dose is defined as the fraction of the nominal dose that is deposited in the lungs or in a specific lung region i (D_{oi}). Therefore, knowledge of the lung (or regional) dose (M_i), the volume of solution available for dissolution (V_i), and the solubility of the drug (C_{si}) are parameters that are required in order to calculate the iBCS dose number.

Professor Qi (Tony) Zhou
IMPH

$$D_{oi} = \frac{(\frac{M_i}{V_i})}{C_{si}}$$

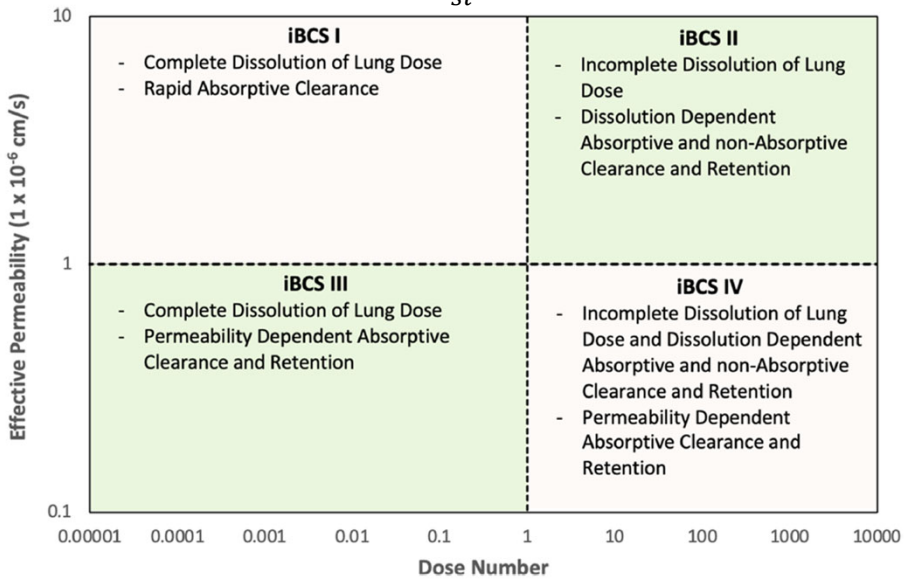


Figure 2. iBCS grid with boundaries delineating high/low permeability and dose number and descriptions of the dissolution and absorption characteristics of drugs falling within the iBCS classes I–IV.

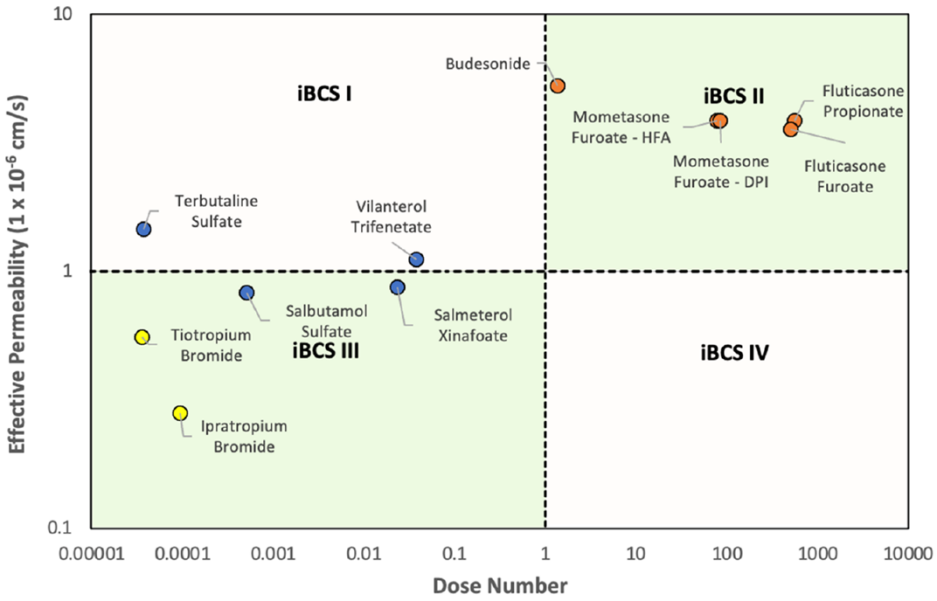


Figure 3. Inhalation biopharmaceutics classification grids, based on the dose number populated with existing drug products identified by therapeutic categories (orange: inhaled corticosteroids, blue: β_2 agonists, and yellow: muscarinic antagonists).

Hastedt, 2023, iBCS3. A biopharmaceutics classification system for orally inhaled drug products

Poorly Soluble Drugs: Amorphous Solid Dispersion

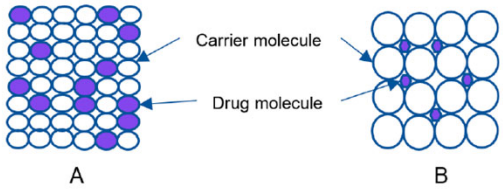


Figure 4. Schematic structure of the solid solution.

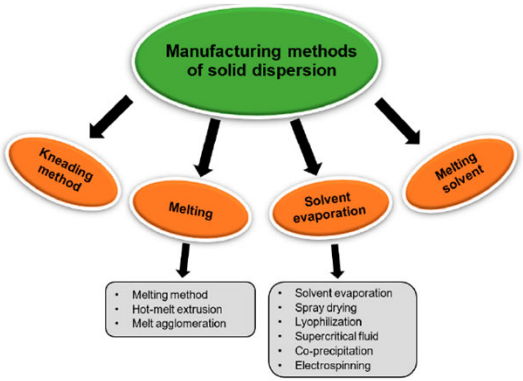


Figure 5. Manufacturing methods of solid dispersion.

Methods	Drugs
Melting/fusion method	Sulfathiazole [39], clotrimazole [43], albendazole [54], tacrolimus [61], fenofibrate [75], furosemide [85], paclitaxel [86], manidipine [88], olanzapine [89], diacerein [90]
Solvent evaporation method	Dutasteride [23], tadalafil [50], glimepiride [53], nimodipine [59], diclofenac [68], azithromycin [91], tectorigenin [92], flurbiprofen [93], cilostazol [94], ticagrelor [95], piroxicam [96], indomethacin [97], loratadine [98], abietic acid [99], efavirenz [100], repagnilide [101], prednisolone [102]
Hot-melt extrusion method	Ritonavir [37], naproxen [46], oleanolic acid [103], efavirenz [104], tamoxifen [105], lafutidine [106], disulfiram [107], bicalutamide [108], itraconazole [109], miconazole [110], glyburide [111]
Lyophilization/Freeze-drying	Nifedipine and sulfamethoxazole [112], celecoxib [113], meloxicam [114], docetaxel [115]
Co-precipitation method	Silymarin [116], celecoxib [117], GDC-0810 [118]
Supercritical fluid method	Ketoprofen [66], irbesartan [119], apigenin [120], carbamazepine [121], glibenclamide [122], carvedilol [123]
Spray-drying method	Nilotinib [124], spironolactone [125], valsartan [126], rebamipide [127], artemether [128], naproxen [129]
Kneading method	Cefixime [67], efavirenz [100], domperidone [130]

PVP: polyvinylpyrrolidone; HPMC: hydroxypropylmethylcellulose; PEG: polyethylene glycol; HPC: hydroxypropylcellulose; HMPC AS: hydroxypropylmethylcellulose acetylsuccinate.

Table 2. List of commercial solid dispersions.

Products	Drugs	Polymers	Company
Afeditab®	Nifedipine	Poloxamer or PVP	Elan Corp, Ireland
Cesamet®	Nabilone	PVP	Lilly, USA
Cesamet®	Nabilone	PVP	Valeant Pharmaceuticals, Canada
Certican®	Everolimus	HPMC	Novartis, Switzweland
Gris-PEG®	Griseofulvin	PEG	Novartis, Switzweland
Gris-PEG®	Griseofulvin	PVP	VIP Pharma, Denmark
Fenoglide®	Fenofibrate	PEG	LifeCycle Pharma, Denmark
Nivadil®	Nivaldipine	HPC/HPMC	Fujisawa Pharmaceuticals Co., Ltd
Nimotop®	Nimodipine	PEG	Bayer
Torcetrapib®	Torcetrapib	HPMC AS	Pfizer, USA
Ibuprofen®	Ibuprofen	Various	Soliqs, Germany
Incivek®	Telaprevir	HPMC AS	Vertex
Sporanox®	Itraconazole	HPMC	Janssen Pharmaceutica, Belgium
Onmel®	Itraconazole	HPMC	Stiefel
Prograf®	Tacrolimus	HPMC	Fujisawa Pharmaceuticals Co., Ltd
Cymbalta®	Duloxetine	HPMC AS	Lilly, USA
Noxafil®	Posaconazole	HPMC AS	Merck
LCP-Tacro®	Tacrolimus	HPMC	LifeCycle Pharma, Denmark
Intelence®	Etravirine	HPMC	Tibotec, Yardley, PA
Incivo®	Etravirine	HPMC	Janssen Pharmaceutica, Belgium
Rezulin®	Troglitazone	PVP	Pfizer, USA
Isoptin SRE-240®	Verapamil	Various	Soliqs, Germany
Isoptin SR-E®	Verapamil	HPC/HPMC	Abbott Laboratories, USA
Crestor®	Rosuvastatin	HPMC	AstraZeneca
Zelboraf®	Vemurafenib	HPMC AS	Roche
Zortress®	Everolimus	HPMC	Novartis, Switzweland
Kalydeco®	Ivacaflor	HPMC AS	Vertex
Kaletra®	Lopinavir and Ritonavir	PVP/polyvinyl acetate	Abbott Laboratories, USA

Tran 2019, Overview of the manufacturing methods of solid dispersion technology for improving the solubility of poorly water-soluble drugs

Poorly Soluble Drugs: Amorphous Solid Dispersion

Table 3. Anticancer drugs investigated for solid dispersions.

Anticancer Drugs	Carriers	Methods	Attributes of Modified Anticancer Drugs	Reference	Years
Bicalutamide	PVP K30	Solvent evaporation	Using PVP K30 as carrier, SD showed the highest cumulative released percentage (about 98% during the initial 10 min) and stability after 6 months	[134]	2006
Docetaxel	HPMC, PEG	Solvent evaporation	The solubility and dissolution of emulsified SD of docetaxel at 2 h were 34.2- and 12.7-fold higher, respectively, compared to the pure conventional drug	[76]	2011
Docetaxel	Poloxamer F68/P85	Freeze-drying	A combination of poloxamer F68 and P85 in the preparation of docetaxel SD not only enhanced solubility, but also improved intestinal permeation	[135]	2016
Etoposide	PEG	Fusion method	The solubility and dissolution of etoposide in SD were higher in comparison with etoposide alone	[136]	1993
Everolimus	HPMC	Co-precipitation	At a ratio of drug to HPMC (1:15), drug release from SD was 75% after 30 min, thereby improving oral absorption of everolimus	[137]	2014
Exemestane	Lipoid® E80S/sodium deoxycholate	Freeze-drying	The exemestane SD showed 4-6-fold increase in absorptive transport compared to the pure drug. In addition, $AUC_{0\text{-}72h}$ of exemestane SD was 2.3-fold higher in comparison with that of drug alone	[138]	2017
Flutamide	PVP K30, PEG, Pluronic F127	Lyophilization	The dissolution of flutamide was higher (81.64%) than the drug alone (13.45%) using poloxamer 407 as a carrier	[77]	2010
Lapatinib	Soluplus, poloxamer 188	Solvent evaporation, hot-melt extrusion	Solubility and dissolution of lapatinib SD were enhanced compared to the drug alone. After 15 min, the drug in SD was released at 92%compared to the drug alone (48%)	[78]	2018
Letrozole	CO_2-menthol	Supercritical fluid	Solubility of letrozole SD using supercritical fluid is 7.1 times higher compared to that of the conventional drug	[139]	2018
Megestrol acetate	HPMC, Ryoto sugar ester L1695	Supercritical fluid	The SD with drug: HPMC: Ryoto sugar ester L1695 ratio of 1:2:1 showed over 95% rapid dissolution within 30 min. In addition, AUC and C_{max} (0-24h) of drug in SD were 4.0- and 5.5-fold higher, respectively, compared to those in pure drug	[140]	2015
Oridonin	PVP K17	Supercritical fluid	The dissolution of oridonin SD significantly increased compared to the original drug. In addition, the absorption of oridonin in SD showed 26.4-fold improvement in BA	[141]	2011
Paclitaxel	Poloxamer 188, PEG	Fusion method	Paclitaxel SD was successfully prepared, and the drug release from SD was higher than that of the drug alone	[86]	2013
Paclitaxel	HPMC AS	Solvent method	The solubility and permeability of paclitaxel were not increased simultaneously through supersaturation in vivo	[133]	2018
Prednisolone	HP-β-CD, PEG, PVP, PEG 4000, MNT, SMP, Cremophor	Solvent evaporation, melting method, kneading method	The in vitro dissolution of prednisolone SD was improved compared with the pure drug	[87]	2011
Raloxifene	PVP K30	Spray-drying	The absorption of raloxifene from SD showed 2.6-fold enhanced BA in comparison with the conventional drug	[142]	2013
Sorafenib	Soluplus	Spray-drying	The C_{max} and $AUC_{0\text{-}48h}$ of sorafenib in SD formulation increased 1.5- and 1.8-fold, resocetuvely, compared with the pure drug	[143]	2015
Tamoxifen	Soluplus	Hot-melt extrusion	The dissolution and BA of tamoxifen in SD were improved compared with the drug alone	[105]	2018
Vemurafenib	HPMC AS	Solvent-controlled precipitation	The BA of vemurafenib in SD was improved 4~5-fold compared to the conventional drug	[144]	2013

HP-β-CD: hydroxypropyl-β-cyclodextrin, MNT: mannitol, SMP: skimmed milk powder.

PVP: polyvinylpyrrolidone; HPMC: hydroxypropylmethylcellulose; PEG: polyethylene glycol; HPC: hydroxypropylcellulose; HMPC AS: hydroxypropylmethylcellulose acetylsuccinate.

Tran 2019, Overview of the manufacturing methods of solid dispersion technology for improving the solubility of poorly water-soluble drugs

Amorphous Solid Dispersions & Crystallinity

Crystallinity: A Complex Critical Quality Attribute of Amorphous Solid Dispersions

Published as part of the Molecular Pharmaceutics virtual special issue "Research Frontiers in Industrial Drug Delivery and Formulation Science".

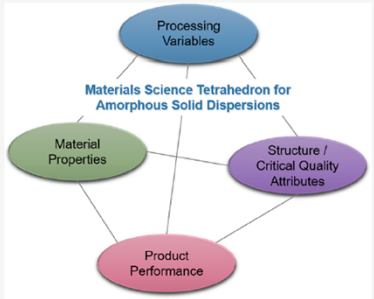
Dana E. Moseson and Lynne S. Taylor*

Cite This: *Mol. Pharmaceutics* 2023, 20, 4802–4825

Read Online

ACCESS | Metrics & More | Article Recommendations

ABSTRACT: Does the performance of an amorphous solid dispersion rely on having 100% amorphous content? What specifications are appropriate for crystalline content within an amorphous solid dispersion (ASD) drug product? In this Perspective, the origin and significance of crystallinity within amorphous solid dispersions will be considered. Crystallinity can be found within an ASD from one of two pathways: (1) incomplete amorphization, or (2) crystal creation (nucleation and crystal growth). While nucleation and crystal growth is the more commonly considered pathway, where crystals originate as a physical stability failure upon accelerated or prolonged storage, manufacturing-based origins of crystallinity are possible as well. Detecting trace levels of crystallinity is a significant analytical challenge, and orthogonal methods should be employed to develop a holistic assessment of sample properties. Probing the impact of crystallinity on release performance which may translate to meaningful clinical significance is inherently challenging, requiring optimization of dissolution test variables to address the complexity of ASD formulations, in terms of drug physicochemical properties (e.g., crystallization tendency), level of crystallinity, crystal reference material selection, and formulation characteristics. The complexity of risk presented by crystallinity to product performance will be illuminated through several case studies, highlighting that a one-size-fits-all approach cannot be used to set specification limits, as the risk of crystallinity can vary widely based on a multitude of factors. Risk assessment considerations surrounding drug physicochemical properties, formulation fundamentals, physical stability, dissolution, and crystal micromeritic properties will be discussed.



KEYWORDS: *amorphous solid dispersion, critical quality attributes, processing, physical stability, dissolution, crystallinity*

Mesoson 2023, crystallinity- a complex critical quality attribute of amorphous solid dispersions

Professor Lynne Taylor
IMPH

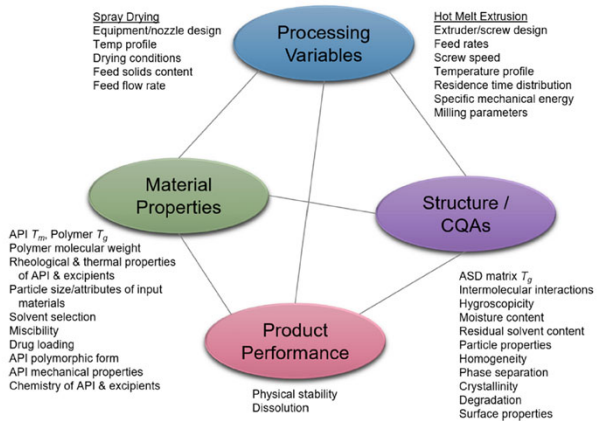


Figure 1. Materials science tetrahedron (MST) as applied to amorphous solid dispersions. The two most popular processing techniques, spray drying and hot melt extrusion, are included to provide examples of key processing variables.

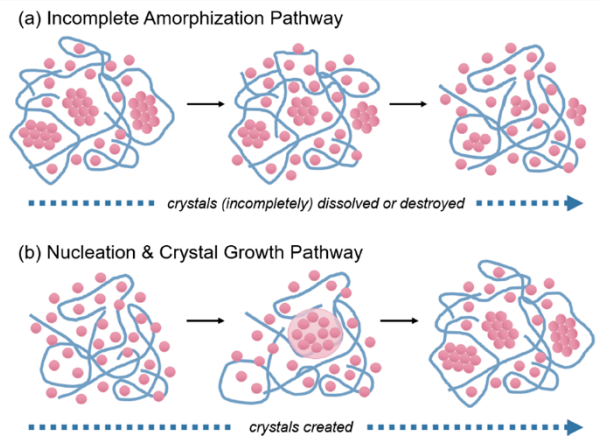


Figure 2. Formation pathways of crystallinity in amorphous solid dispersions: (a) incomplete amorphization, (b) nucleation and crystal growth.

Oral Delivery of Poorly-Soluble Drugs

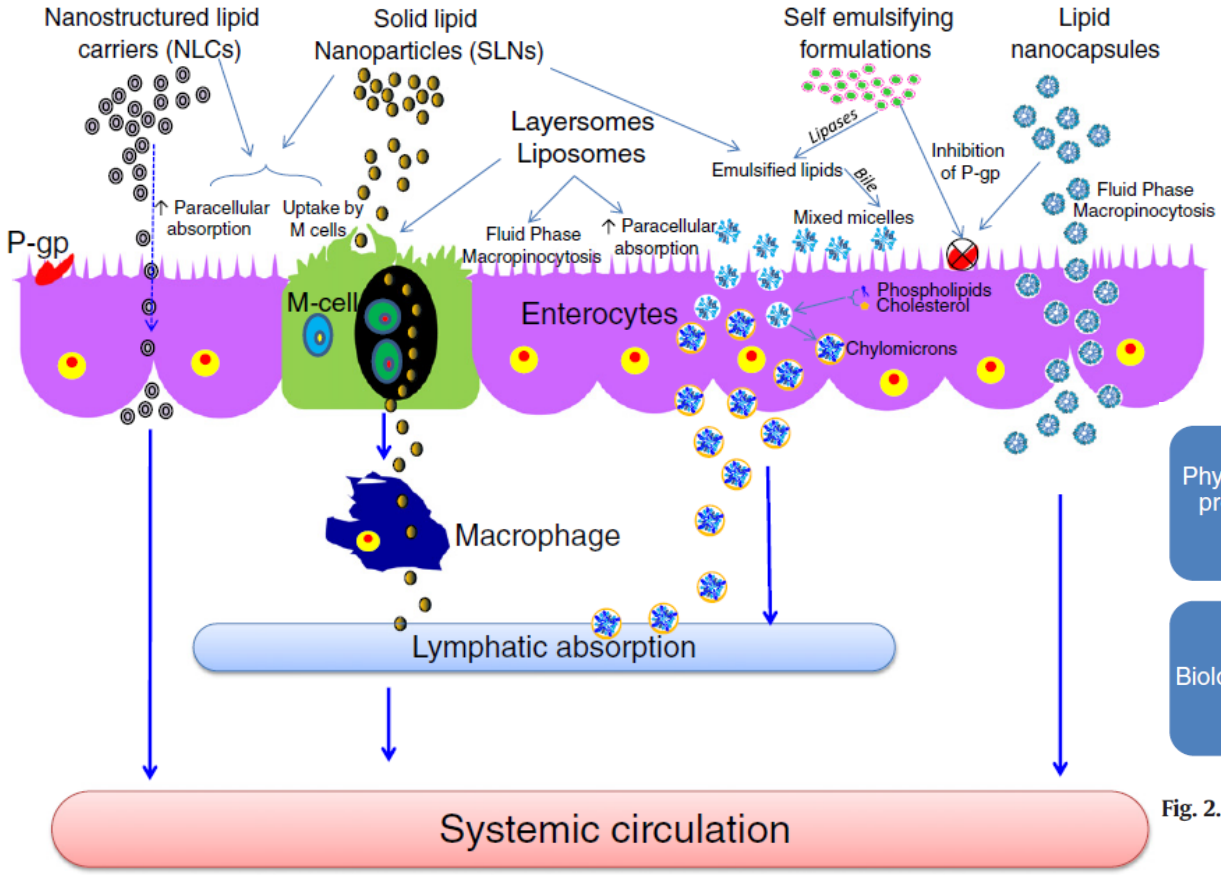


Fig. 11. Absorption mechanisms implemented by lipidic nanocarriers for improving the oral bioavailability of drug substances.

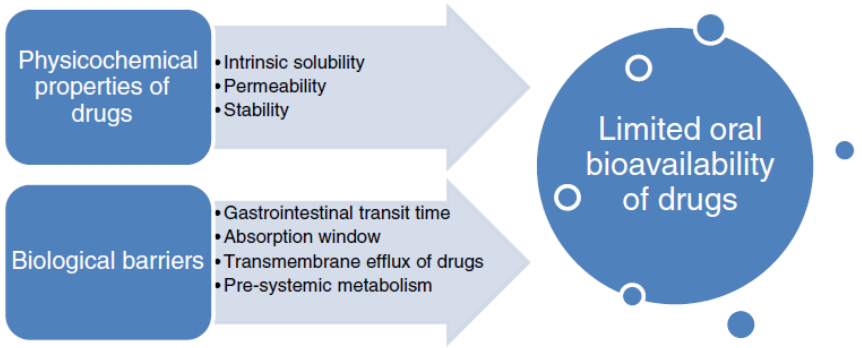


Fig. 2. Schematic representation of the various challenges to the oral delivery of drugs.

Oral delivery of anticancer drugs: Challenges and opportunities.
Kaushik Thanki, Rahul P. Gangwal, Abhay T. Sangamwar, Sanyog Jain. J. Controlled Rel. 170: 15-40, 2013.

Biological Barriers Everywhere

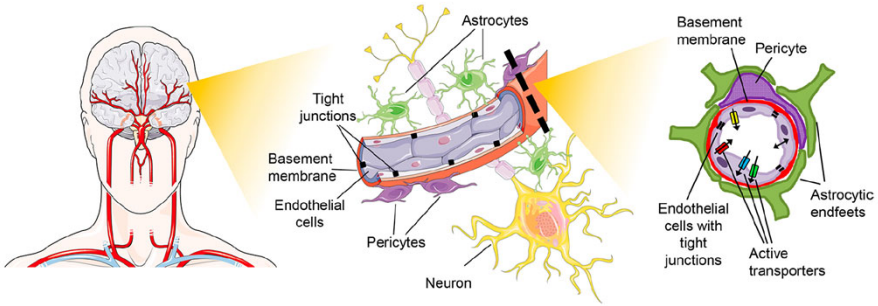


Figure 1. Overview of the multicellular structure of the BBB.

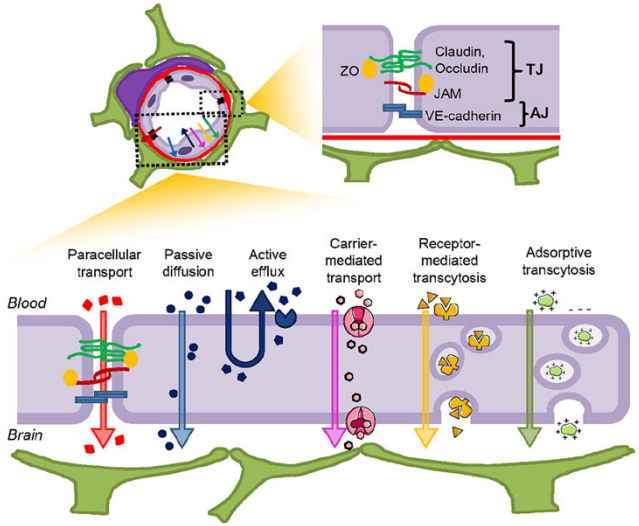


Figure 2. Junctional complexes of the BBB and permeation pathways across it.

Parrasia 2022, Peptides as pharmacological carriers to the brain-promises, shortcomings and challenges

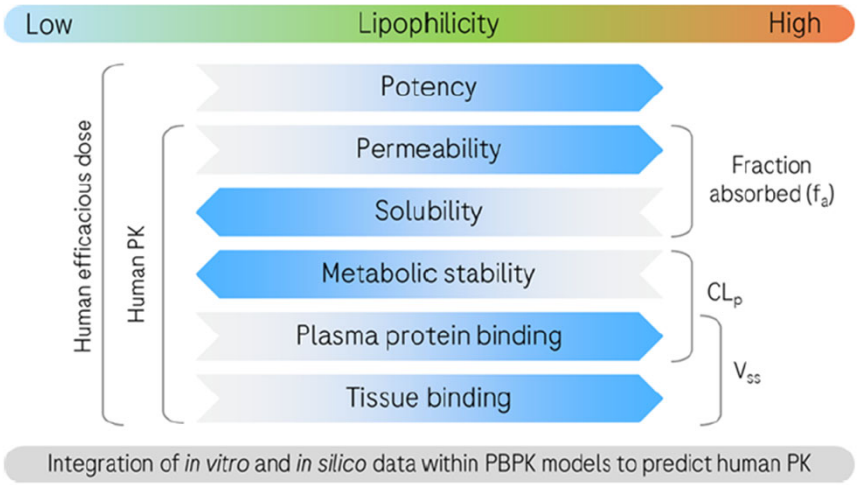


Figure 1. Modulation of lipophilicity causes complex changes in compound PK. Integrative PBPK models can provide a way to predict these effects and estimate an efficacious dose.

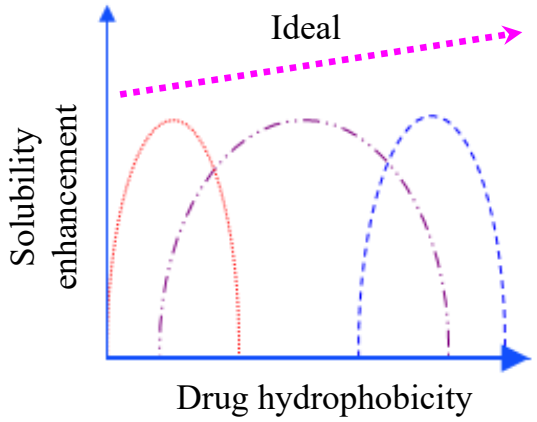
Parrott 2022, Can we predict clinical pharmacokinetics of highly lipophilic compounds by integration of machine learningv

Solubilization Methods for Poorly-Soluble Drugs

Manipulating Solubility by Changing

Solid state properties	Solute-solvent interactions
Particle size	pH control
Polymorphs	Ionic additives
Solvates	Co-solvents
Amorphous forms	Surfactants
	Complexation
	Polymer micelles
	Hydrotropes

Each solubilization method has advantages and limitations.



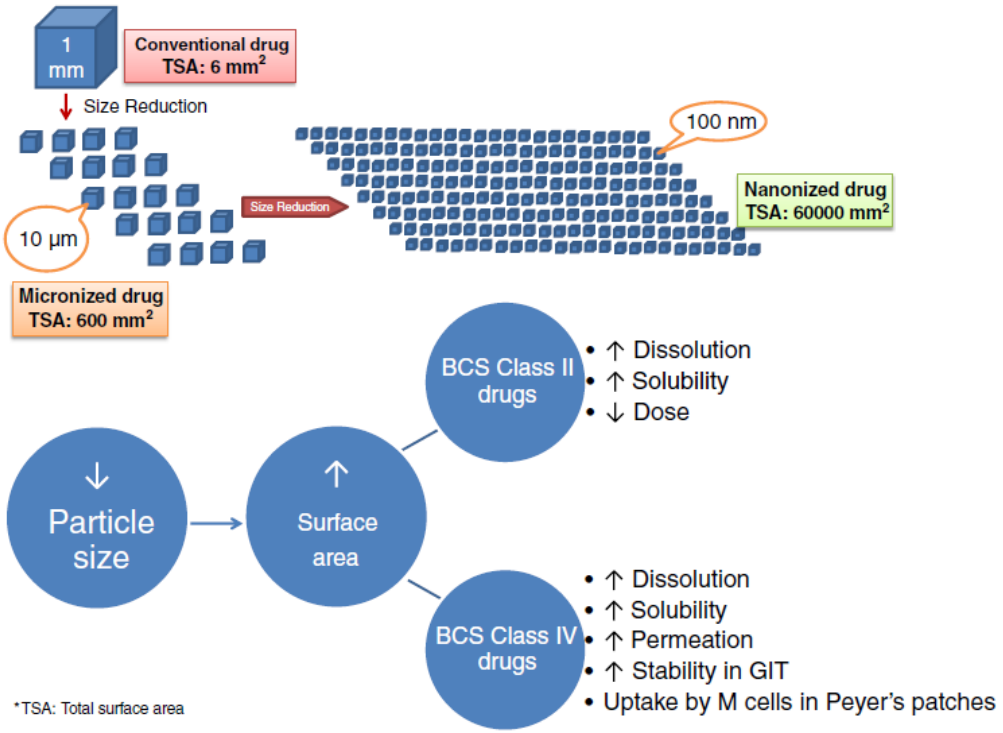
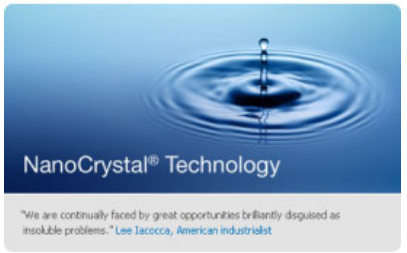


Fig. 6. Mechanistic representation of absorption *via* nanocrystals.

Nanocrystal Formulations in Clinical Use

1. Rapamune (sirolimus, Wyeth 2000)
2. Emend (aprepitant, Merck 2003)
3. TriCor (fenofibrate, Abbott 2004)
4. Megace (megestrol acetate, Par 2005)
5. Triglide (fenofibrate, Skye Pharma 2005)
6. Invega Sustenna (paliperidone palmitate, Janssen 2009)



their routine use in current marketed products. So far, only six commercial products, namely Rapamune (sirolismus, former Wyeth), Emend (aprepitant, Merck), TriCor (fenofibrate, Abbott), Megace (megestrol acetate, Par Pharmaceutical), Invega Sustenna (paliperidone palmitate, Janssen) and Triglide (fenofibrate, Skye Pharma) have resulted from nanocrystal technology [14] and approximately ten solid dispersion

Peltonen, L., J. Hirvonen, Pharmaceutical nanocrystals by nanomilling: critical process parameters, particle fracturing and stabilization methods, J. Pharm. Pharmacol. 62(11) 1569-1579.

Nanocrystals for Improving Oral Bioavailability of Drugs

Rapamune (sirolimus) Tablets and Oral Solution — Wyeth 2000

EMEND (aprepitant) — Merck 2003

TriCor 145 mg fenofibrate tablets & 48 mg — Abbott 2004

MEGACE ES megestrol acetate — Par 2005

Triglide (fenofibrate) tablets 50 mg — Skye Pharma 2005

NEW ONCE-MONTHLY INVEGA SUSTENNA paliperidone palmitate extended-release injectable suspension — Janssen 2009

Review article

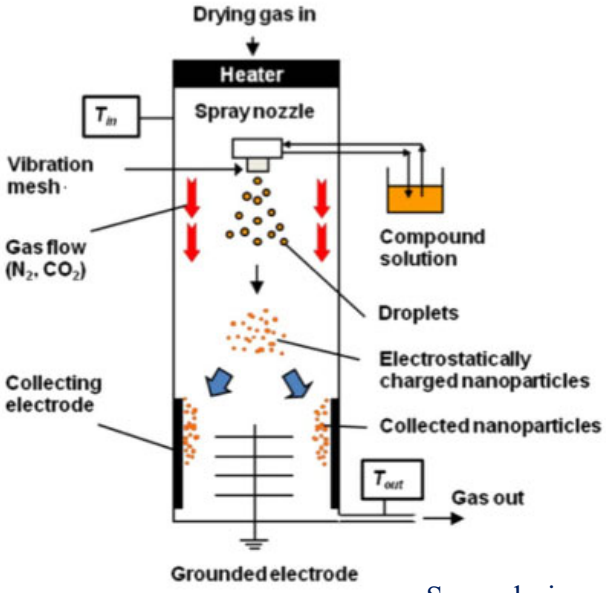
Nanosizing techniques for improving bioavailability of drugs

Raida Al-Kassas*, Mahima Bansal, John Shaw

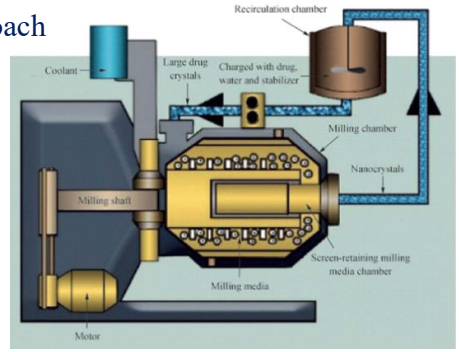
School of Pharmacy, Faculty of Medical and Health Sciences, The University of Auckland, Private Bag 92019, Auckland 1142, New Zealand

Bottom-Up Approach

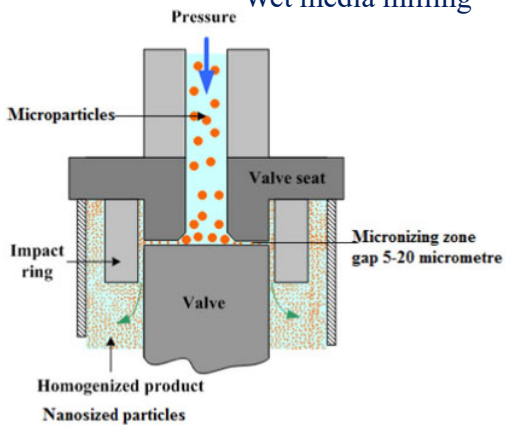
Top-Down Approach



Spray drying



Wet media milling



High pressure homogenizer

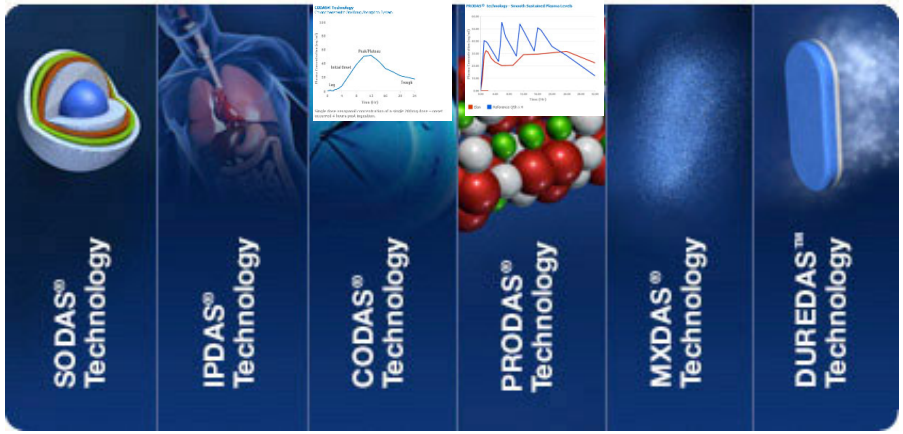
R. Al-Kassas, M. Bansal, J. Shaw. Nanosizing techniques for improving bioavailability of drugs. Journal of Controlled Release, 260 (2017) 202-212.

Oral Extended release formulations

Spheroidal Oral DAS

Programmable Oral DAS

Dual Release DAS



Intestinal Protective DAS

MatriX Drug Absorption System

24 hour AVINZA® (morphine sulfate extended-release capsules)

Once-Daily NAPRELAN® (naproxen sodium) Controlled-Release Tablets Utilizing the IPDAS® Biphasic System

ONCE-DAILY Focalin® XR® dexmethylphenidate HCl

ampyra® (dalfampridine) D RELEASE TABLETS 10 mg

LUVOX® CR

Ritalin® LA
Methylphenidate HCl

Cardizem CD
Diltiazem HCl

Once at bedtime Controlled onset Verelan® PM (verapamil HCl) extended-release capsules

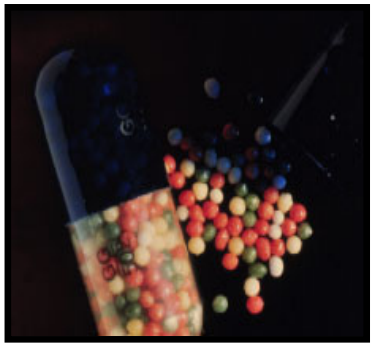
Chronotherapeutic Oral DAS

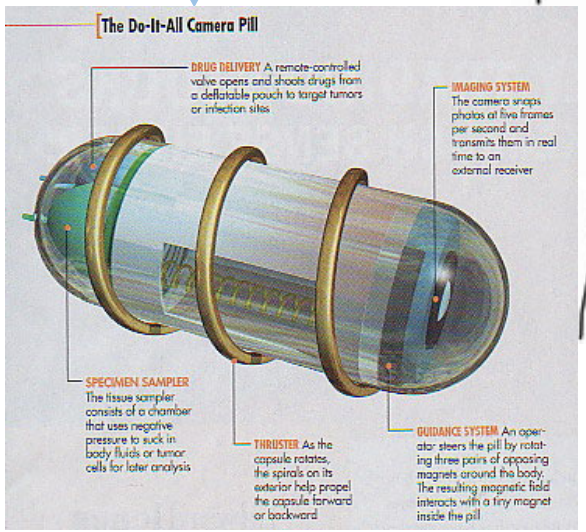
BID.
Hydrophilic matrix-forming polymers

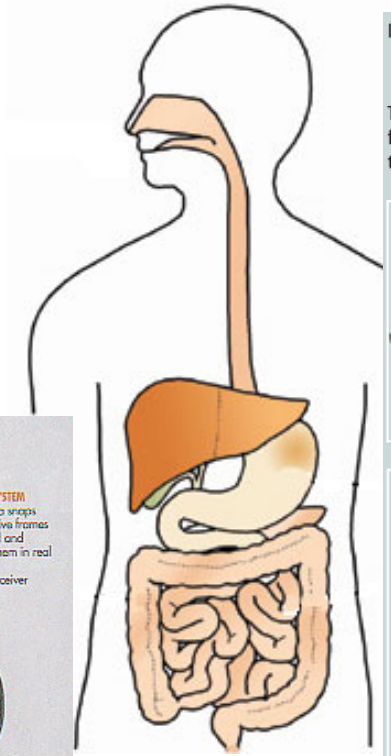
DAS: Drug Absorption System

Seroquel (Quetiapine)
AstraZeneca: $5 Billion
Depressive disorder

Oral Delivery: Targeting to GI Tract







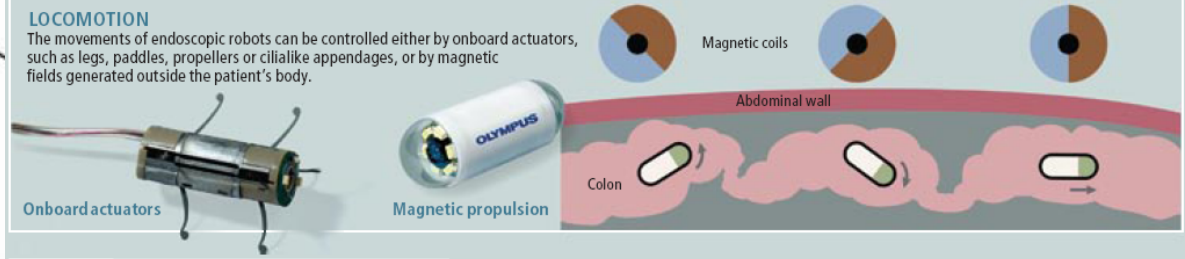
[IN THE WORKS]

MINI BOTS FOR A WIDE RANGE OF JOBS

To make miniature robots that can operate in the digestive tract, engineers must find ways of wirelessly controlling their locomotion and fine movements. And they must fit the required tools, imaging sensors and power supply into a capsule small enough for a patient to swallow. Here are some examples of the diverse tasks engineers want tiny robots to do and the ways they are trying to overcome the technical challenges.

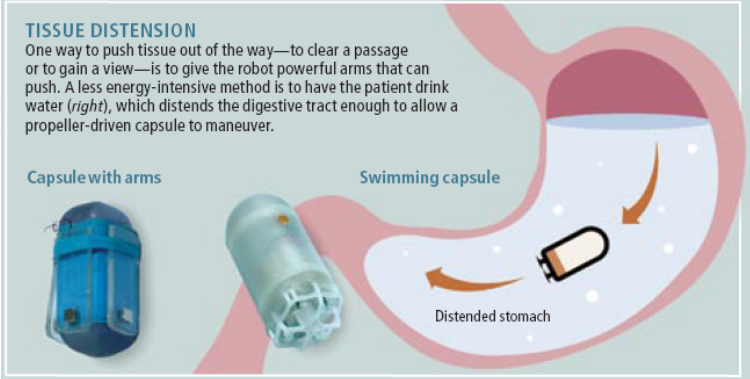
LOCOMOTION

The movements of endoscopic robots can be controlled either by onboard actuators, such as legs, paddles, propellers or cilialike appendages, or by magnetic fields generated outside the patient's body.



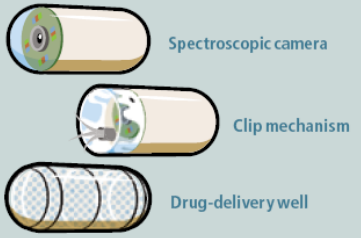
TISSUE DISTENSION

One way to push tissue out of the way—to clear a passage or to gain a view—is to give the robot powerful arms that can push. A less energy-intensive method is to have the patient drink water (*right*), which distends the digestive tract enough to allow a propeller-driven capsule to maneuver.



DIAGNOSIS/TREATMENT

A capsule can carry a wide range of tools: a spectroscopic camera that sees cells underneath the surface layer of tissue; a clip for taking a tissue biopsy; or a well that holds a dose of medication.



Remote control devices

Scientific American. August 2010

Oral Delivery: Gastric Retention Devices

Hwang 1998, Gastric retentive drug delivery systems

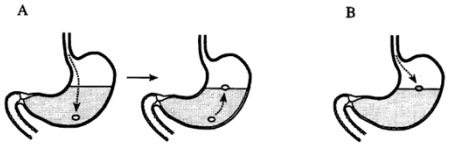


FIGURE 5. Devices with densities lower than 1 can be used to make systems floating in the stomach. The density of a device can be lowered after administration to the stomach (A), or can be made of lower density materials from the beginning (B).

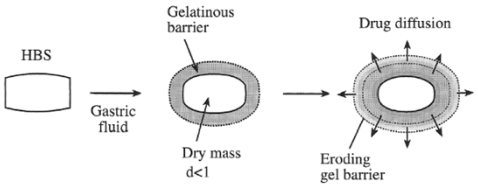


FIGURE 6. Description of the hydrodynamically balanced system (HBS). Diffusion of the gastric fluid to a dried HBS system results in a formation of the gelatinous polymer layer. Drug is released by diffusion and erosion of the gel barrier.

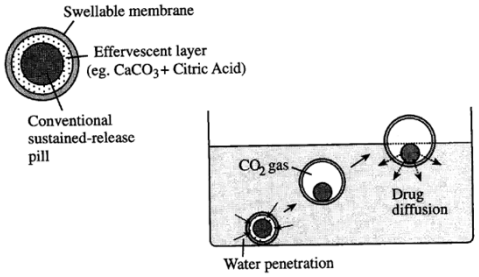


FIGURE 7. Structural characteristics (left) and floating mechanism (right) of the gas-generating microballoon system. The right figure shows penetration of water into the microparticle and generation of CO_2 to make the system float. From Ichikawa.[14]

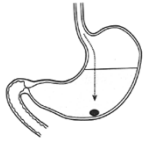


FIGURE 8. Settlement of a high-density device to the bottom of the stomach.

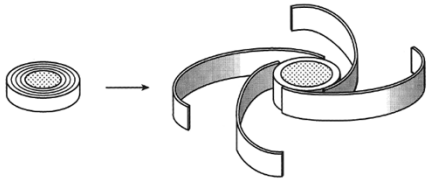


FIGURE 12. The system with the coiled arms (left) can unfold the arms (right) in the stomach. The expanded form is expected to resist gastric retention. From Curatolo and Lo.[107]

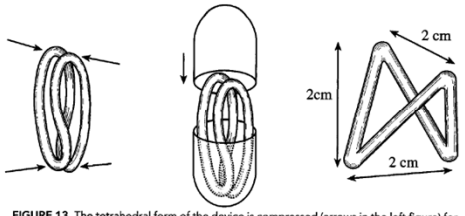


FIGURE 13. The tetrahedral form of the device is compressed (arrows in the left figure) for encapsulation (center). In the stomach, the preferred tetrahedral form (right) is restored for extended gastric retention. From Caldwell et al.[108]

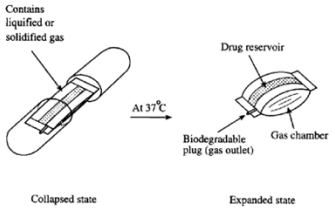


FIGURE 15. An example of an expandable device based on gas evaporation. The expanded device will be deflated upon removal of the plug by biodegradation. From Michaels et al.[118]

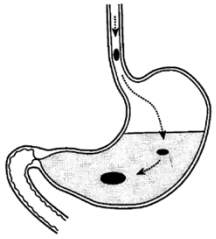


FIGURE 14. The expandable device can swell in the stomach either by absorbing water from the gastric juice or by evaporation of solidified or liquefied gas present in the device.

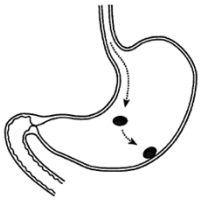


FIGURE 9. Attachment of a mucoadhesive dosage form to the mucus layer in the stomach.

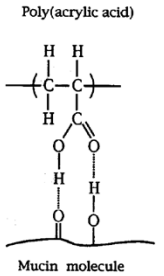


FIGURE 10. Interaction between poly(acrylic acid) and mucin molecules through numerous hydrogen bonding.

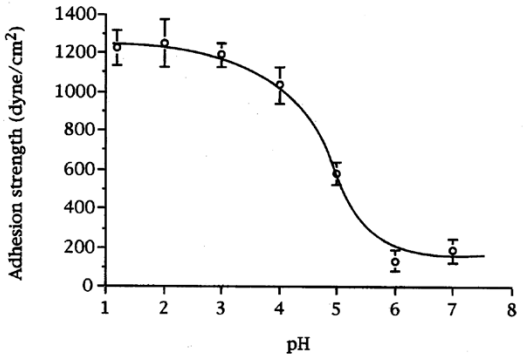


FIGURE 11. Mucoadhesive strength of polycarbophil to rabbit gastric tissue as a function of pH. From Park and Robinson.[97]

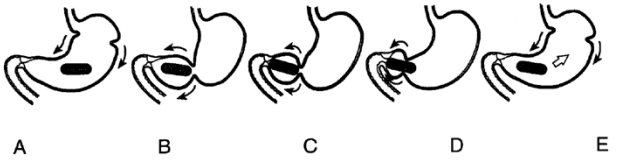


FIGURE 18. A sequence showing the movement of a swollen hydrogel to the pylorus by gastric contractions and retropulsion back to the body of the stomach as visualized by ultrasound and fluoroscopic imaging. From Shalaby et al.[126]

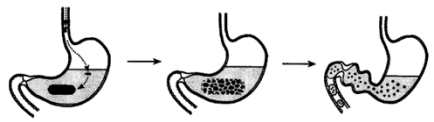


FIGURE 17. A dried superporous hydrogel swells to a huge size in the stomach (A). As the drug is released, the swollen hydrogel can undergo degradation (B) and eventually is emptied from the stomach (C).

Oral Delivery: Gastric Retention Devices

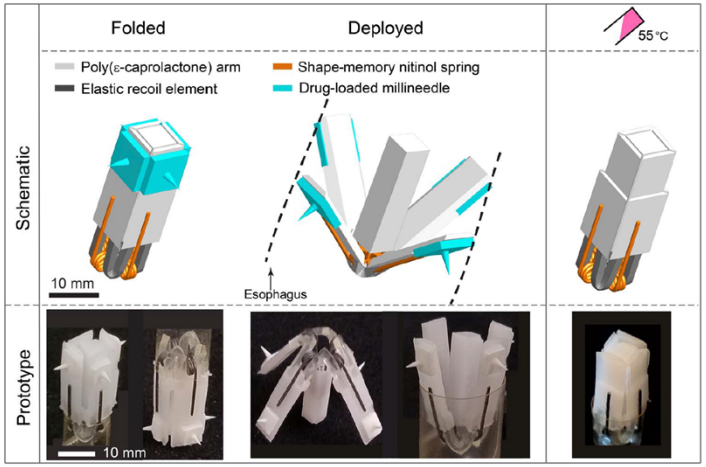


Fig. 2. Esophageal flower-like system. Schematic and prototype images of the flower-like system, illustrating the configurations when folded (before administration), deployed in the esophagus, and folded again following temperature triggering. The components of the design including polymeric arms (light gray), elastic recoil elements (dark gray), nitinol springs (orange), and dissoluble millineedles (green) are shown.

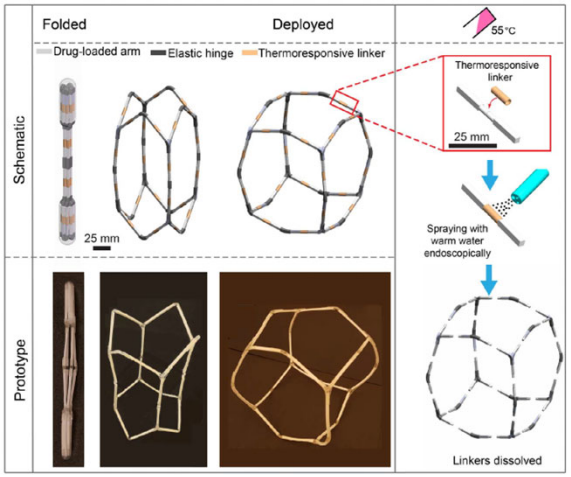
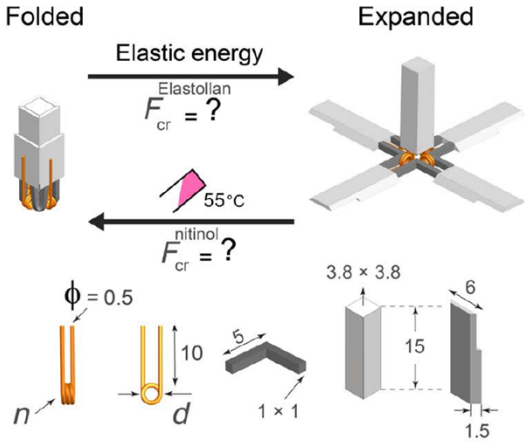
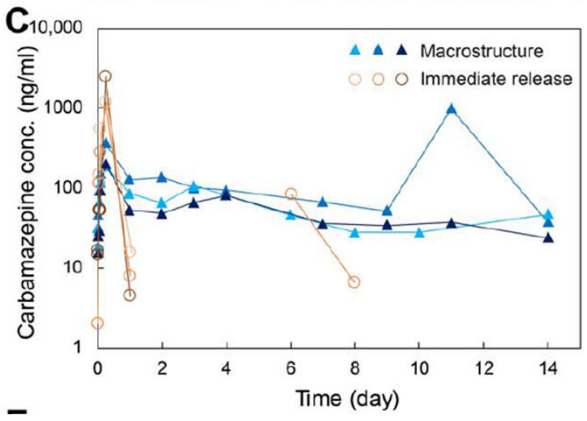


Fig. 4. Flexible mechanical metamaterial as a macrostructure dosage form. The schematic and prototype images of the metamaterial dosage form illustrating the sequence of deployment in stomach and the building components including drug-carrying arms (light gray), elastic hinges (dark gray), and TRLs (orange). The right panel shows temperature-triggered configuration by endoscopically applying warm water (55°C) to trigger the disassembly.





Babaee 2019, Temperature-responsive biometamaterials for gastrointestinal applications

In vivo temperature testing
The temperature in the esophagus and stomach during administration of warm water wasmeasured in a large animal model (three Yorkshire pigs)

Oral Peptide Delivery

While oral delivery of peptide drugs using absorption enhancers provides convenience to patients, the high cost of making synthetic peptides presents a considerable challenge in manufacturing cost due to poor oral bioavailability (usually ~1% or less) and a ~100-fold increase in weekly dose requirements when switching from the typical dose of subcutaneous (SQ) administration (1 mg) to oral (98 mg) [1–4]. A recent article reviewed the current status, challenges, and translational considerations of the oral delivery of biologics, including nucleic acid and protein therapeutics [5]. Despite significant advances in oral drug delivery systems, the oral delivery of biologics still requires a series of new scientific breakthroughs [5].

1. Brayden DJ, Maher S. Transient permeation enhancer® (TPE®) technology for oral delivery of octreotide: a technological evalu- ation. Expert Opin Drug Deliv 2021;10:1501–12.
2. Maher S, Brayden DJ. Formulation strategies to improve the efficacy of intestinal permeation enhancers. Adv Drug Deliv Rev 2021;177:113925. https://doi.org/10.1016/j.addr.2021.113925
3. Kim JC, Park EJ, Na DH. Gastrointestinal permeation enhancers for the development of oral peptide pharmaceuticals. Pharmaceuticals (Basel) 2022;15:1585. https://doi.org/10.3390/ph15121585
4. Brayden DJ. An update on oral administration of peptides to achieve systemic delivery. Am Pharm Rev 2023. https://www.ame ricanpharmaceuticalreview.com/Featured-Articles/595225-An-Update-on-Oral-Administration-of-Peptides-to-Achieve-Systemic-Delivery/
5. Ding S, Alexander E, Liang H et al. Synthetic and biogenic materials for oral delivery of biologics: from bench to bedside. Chem Rev 2025;125:4009–68. https://doi.org/10.1021/acs.chemrev.4c00482.

Table 1 also highlights the significance of introducing new technologies, such as PEGylation. Once PEGylation [the grafting of poly(ethylene glycol) (PEG) to drugs] was introduced as a safe and effective method, it was applied to various formulations. One notable formulation was Onpattro, which used PEGylated lipid nanoparticles for the delivery of small interfering RNA (siRNA). The same formulation was used to develop the COVID-19 vaccine in 2021. Imagine a situation where no formulation was available to deliver the messenger RNA (mRNA) used for making the vaccine. The availability of drug delivery vehicles approved by the US Food and Drug Administration (FDA) accelerated the clinical application.

Table 1. The first formulations approved by the US FDA introducing new technologies.

Formulation	Product	Year
Dissolution-controlled oral formulation	Spansule®	1952
Oil-based long-acting injectable	Prolixin®	1972
Diffusion-controlled ocular formulation	Ocusert®	1974
Osmosis-controlled oral formulation	OROS®	1975
Ion exchange-controlled oral formulation	Delsym®	1982
PLGA-based long-acting injectable	Lupron Depot®	1989
PEGylated protein	Adagen®	1990
PEGylated caster oil micelle	Taxol®	1994
PEGylated liposome	Doxil®	1995
Ab-drug conjugate	Mylotarg™	2000
Nanocrystals	Rapamune®	2000
Amorphous solid dispersion	Kaletra®	2000
Albumin–drug complex	Abraxane®	2005
PEGylated small molecule	Movantik®	2014
CAR-T gene therapy	Kymriah®	2017
PEGylated lipid nanoparticle	Onpattro®	2018

Otte 2025, Challenges and innovations in long-acting injectable formulations: Can formulation design space be rationalized?

Oral Peptide Delivery

Oral supramolecular drug delivery systems (SDDSs)

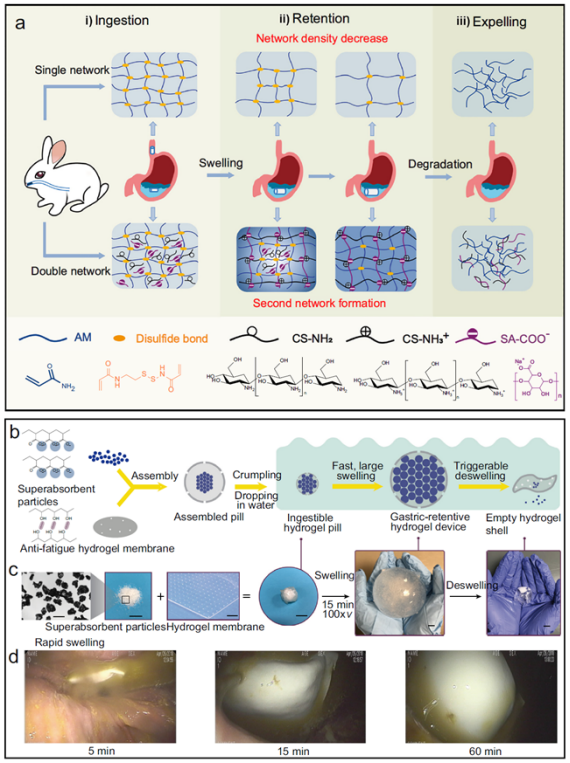


Fig. 4. (a) Design concept of swelling SDDSs. (b-d) Schematic representation and photographs illustrating the fabrication process and working mechanism of the hydrogel device.

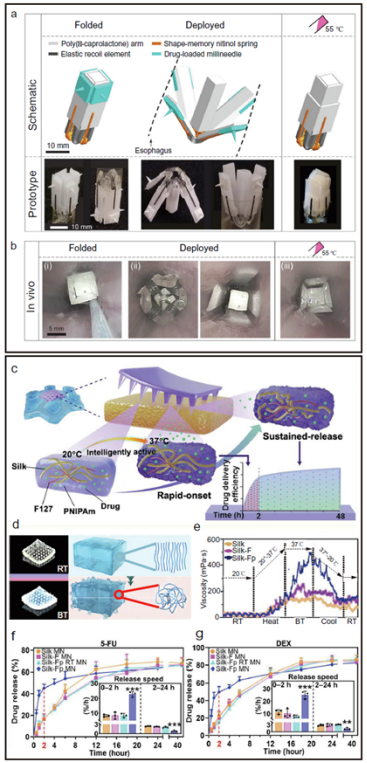


Fig. 5. Temperature-responsive SDDSs in oral administration.

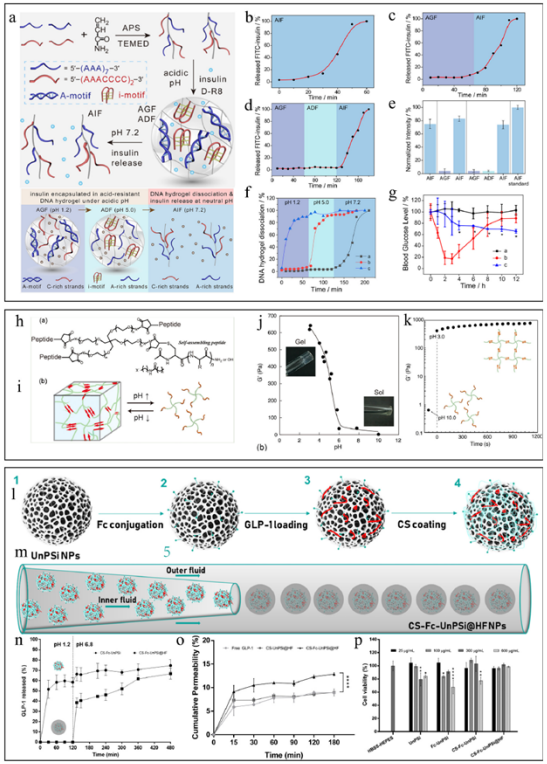


Fig. 7. pH-responsive SDDSs.

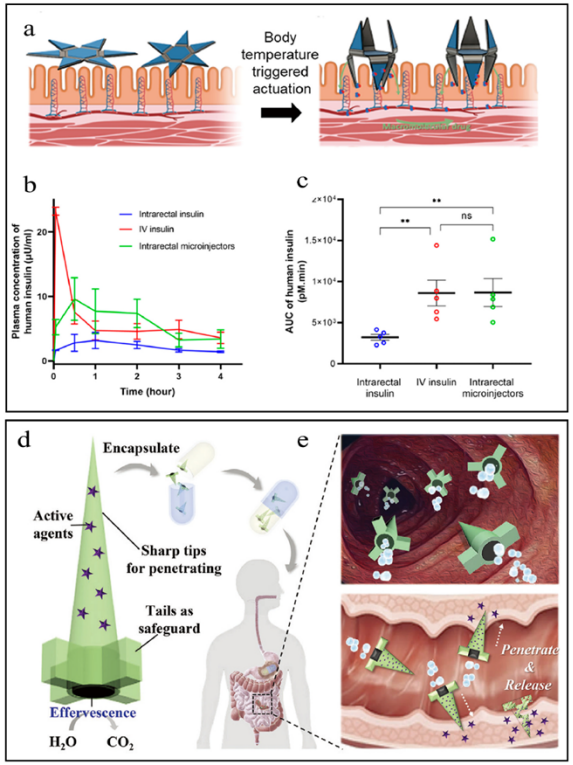


Fig. 9. Stimulation-responsive oral microneedle SDDSs.

Chen 2025, Supramolecular oral delivery technologies for polypeptide-based drugs

Oral Delivery: Biotherapeutics

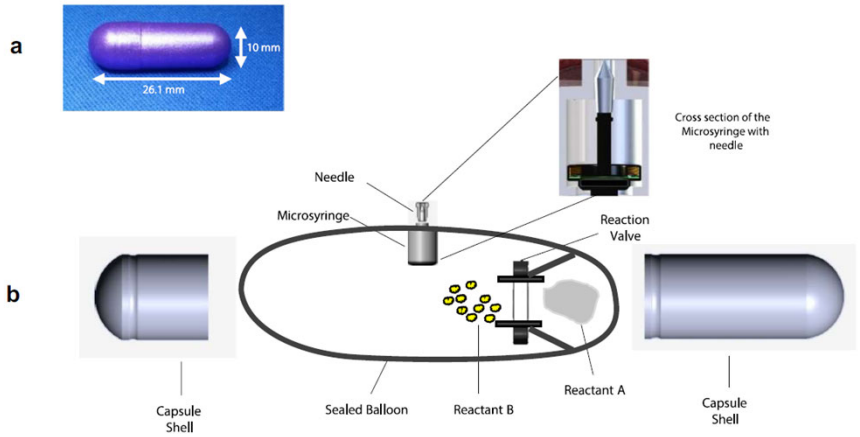


Fig. 1 RP design. **a** Fully assembled enteric-coated RP. **b** Schematic drawing showing various parts and components of the RP. Inset shows the microsyringe containing the needle with the drug microtablet which gets injected into the jejunal wall. The microtablet and needle are aseptically manufactured in an isolator and hermetically sealed inside a drug chamber which is then inserted in the microsyringe

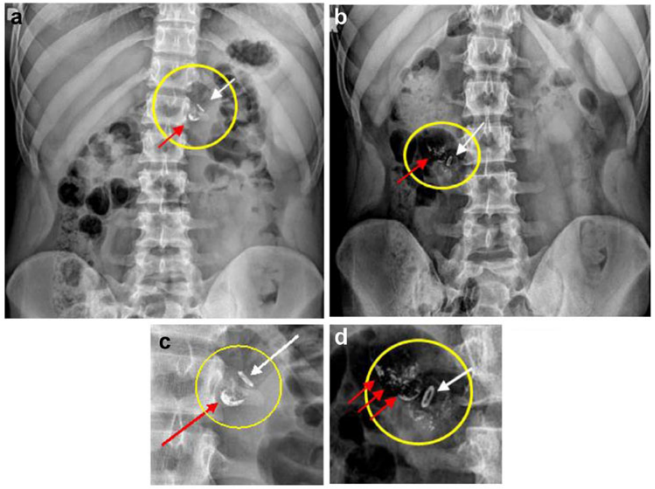
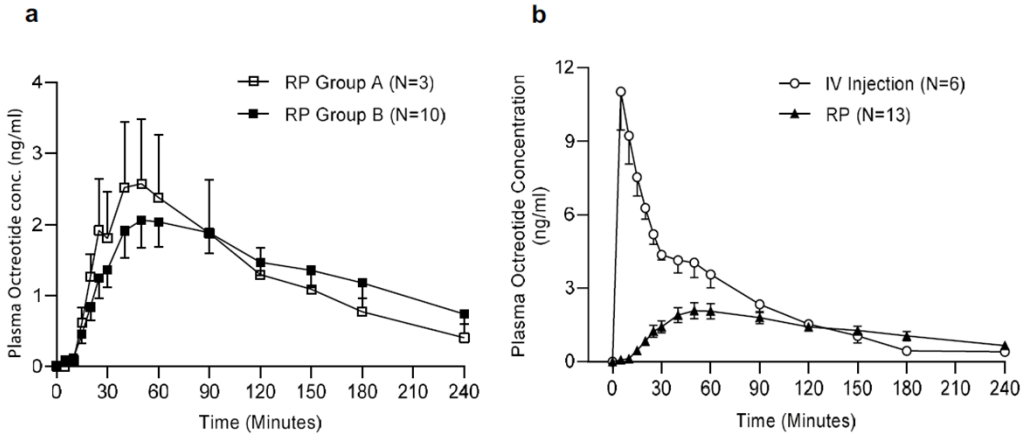


Fig. 3 **a** Representative X-ray image of an intact RP residing in the stomach (encircled) showing a radio-opaque ring (which is part of the device) at one end of the device (white arrow) and barium sulfate powder inside the capsule shell at the other end (red arrow). **b** Representative X-ray image of a deployed RP in the small intestine (encircled). The radio-opaque ring (white arrow) is part of the device whereas barium sulfate is dispersed inside the intestinal lumen (red arrows). **c** Magnified encircled area from **a**. **d** Magnified encircled area from **b**



PK parameters for Octreotide administered via IV injection and RP

Group	C_{max} (ng/mL)	T_{max} (min)	$AUC_{last/Dose}$ ((min*ng/mL)/(μg/kg))	Bioavailability (% F)
IV Sandostatin (N=6)	11.1 ± 1.6	5	389 ± 22	NA
RP (N=13)	2.4 ± 0.3	50	226 ± 30	65 ± 9

Fig. 5 PK of octreotide in healthy human volunteers. **a** Time-course of changes in plasma concentrations of octreotide delivered via RP A and B. **b** Time-course of changes in plasma octreotide levels following octreotide administration either IV ($N=6$) or orally via the RP ($N=13$, groups A and B combined) in healthy human volunteers. Numbers in the table below the graphs are PK parameters for the IV and RP groups. Data are presented as means ± SE

Dhalla 2022, A robotic pill for oral delivery of biotherapeutics

GLP-1 Agonist: Diabetes Drugs and Weight Loss

Are there any type 2 diabetes drugs that can help people lose weight and lower their blood sugar? Are there side effects? (M. Regina Castro, M.D.)

There's a class of type 2 diabetes drugs that not only improves blood sugar control but may also lead to weight loss. This class of drugs is commonly called glucagon-like peptide 1 (GLP-1) agonists. Weight loss can vary depending on which GLP-1 drug you use and your dose. Studies have found that all GLP-1 drugs can lead to weight loss of about 10.5 to 15.8 pounds (4.8 to 7.2 kilograms, or kg) when using liraglutide. Studies found people using semaglutide and making lifestyle changes lost about 33.7 pounds (15.3 kilograms) versus 5.7 pounds (2.6 kilograms) in those who didn't use the drug.

Diabetes drugs in the GLP-1 agonists class are generally taken by a shot (injection) given daily or weekly and include:

- Dulaglutide (Trulicity) (weekly)
- Exenatide extended release (Bydureon bcise) (weekly)
- Exenatide (Byetta) (twice daily)
- Semaglutide (Ozempic for Type 2 diabetes) (Wegovy for weight loss) (weekly)
- Liraglutide (Victoza, Saxenda) (daily)
- Lixisenatide (Adlyxin) (daily)
- Semaglutide (Rybelsus) (taken by mouth once daily)

It's not clear how the GLP-1 drugs lead to weight loss. Doctors do know that GLP-1s appear to help curb hunger. These drugs also slow the movement of food from the stomach into the small intestine. As a result, you may feel full faster and longer, so you eat less.

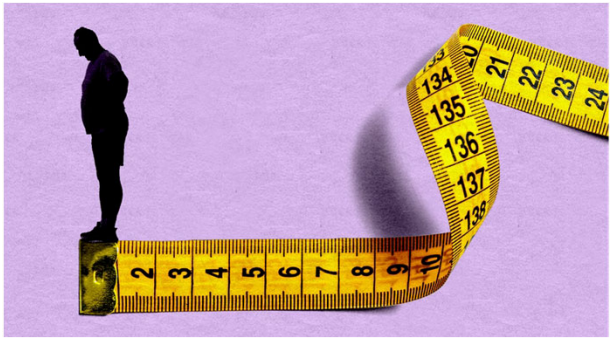
Zepbound
Tirzepatide: A dual GIP/GLP-1 receptor co-agonist.
FDA approved tirzepatide for weight loss (Eli Lilly).
(GIP: insulinotropic polypeptide)

https://www.mayoclinic.org/diseases-conditions/type-2-diabetes/expert-answers/byetta/faq-20057955
Haelle 2023, New obesity drugs are coming

Weight loss triggers a set of powerful physiological changes in the body, which evolved over millions of years to keep us alive through periods of food scarcity. "Everybody plateaus," says Jamy Ard, an obesity doctor at Wake Forest University. Exactly when varies quite a bit from person to person, but it happens after losing a certain percentage of body weight—meaning some people might plateau while still meeting the criteria for obesity.

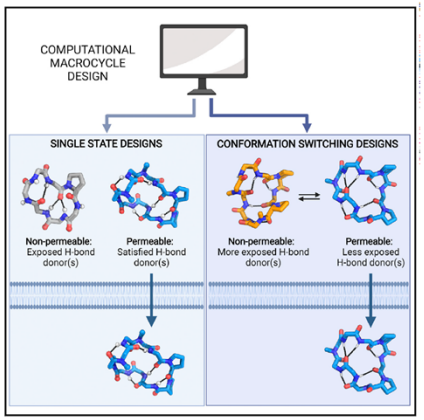
For Wegovy, it's after losing, on average, 15 percent, usually more than a year into starting the drug. For Zepbound, it's about 20 percent. These numbers are higher than is sustainable through diet and exercise alone, but they also do not reach the 30 percent achievable via the gold standard of bariatric surgery.

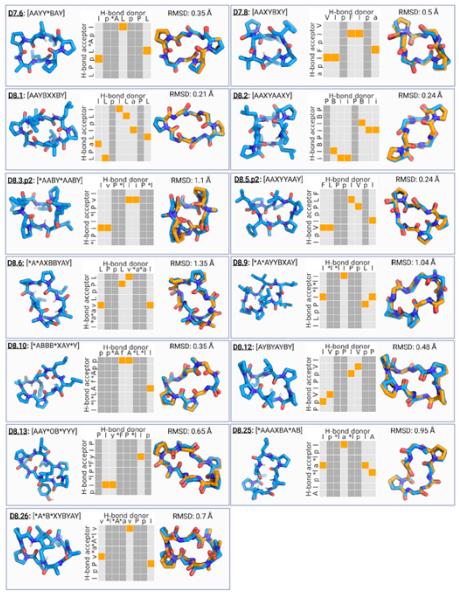
https://www.theatlantic.com/health/archive/2024/01/why-you-will-stop-losing-weight-ozempic/677148/?utm_source=apple_news



The downside to GLP-1 drugs is that all but one has to be taken by a shot. And, like any drug, there is a risk of side effects, some serious. More common side effects often improve as you continue to take the drug for a while. Some of the more common side effects include: Nausea, vomiting, and diarrhea.

Oral Peptide Delivery





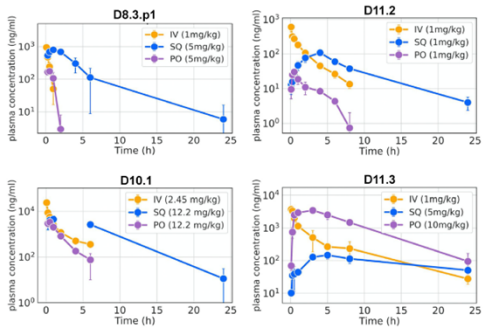


Figure 5. Designed macrocycles are orally bioavailable in vivo in rodent models
Plasma concentration of unmodified full-length peptides measured after intravenous (IV), subcutaneous (SQ), and oral (PO) administration in mice (D8.3.p1, D10.1, and D11.3) and rats (D11.2) (n = 3 mice per dosing route for D8.3.p1, D10.1, and D11.3 and n = 3 rats per dosing route for D11.2). D8.3.p1 and D10.1 were studied in female BALB/c mice, D11.2 was studied in male Sprague Dawley (SD) rats, and D11.3 was studied in male swiss albino mice.
See also Data S5.

Bhardwaj 2022, Accurate de novo design of membrane-traversing macrocycles

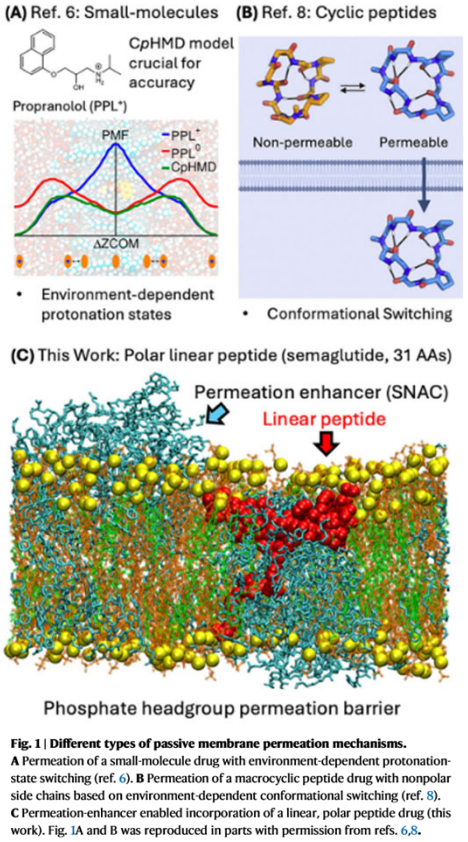


Fig. 1 | Different types of passive membrane permeation mechanisms. **A** Permeation of a small-molecule drug with environment-dependent protonation-state switching (ref. 6). **B** Permeation of a macrocyclic peptide drug with nonpolar side chains based on environment-dependent conformational switching (ref. 8). **C** Permeation-enhancer enabled incorporation of a linear, polar peptide drug (this work). Fig. 1A and B was reproduced in parts with permission from refs. 6,8.

Professor Severin Schneebeli
IMPH

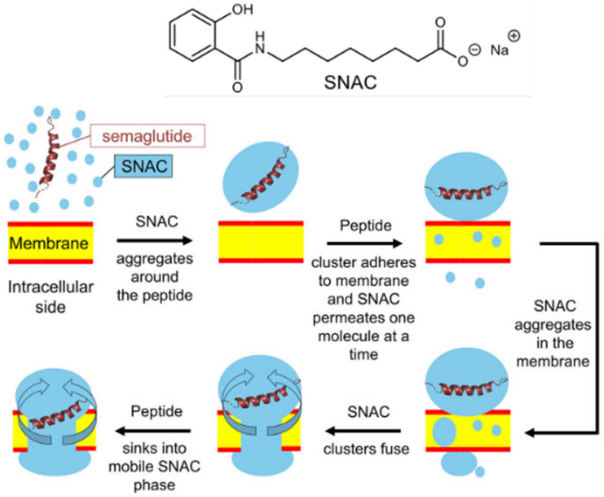


Fig. 7 | A possible molecular mechanism for SNAC-assisted membrane permeation of semaglutide. Curved arrows represent the movement of mobile SNAC molecules.

Colston 2025, Permeation enhancer-induced membrane defects assist the oral absorption of peptide drugs

Oral Delivery: Biotherapeutics

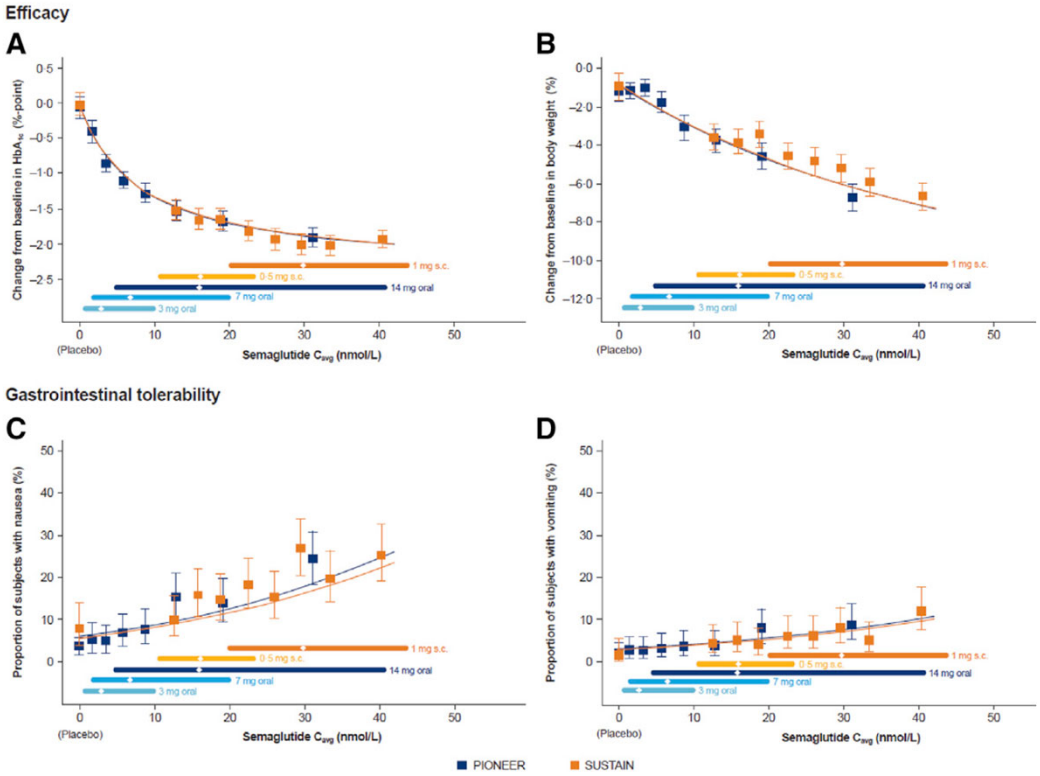


Figure 4. Efficacy and tolerability by semaglutide exposure in the PIONEER and SUSTAIN trials. Data are means and 95% CIs at week 26 for PIONEER and week 30 for SUSTAIN. Exposure is presented as quantiles of Cavg for semaglutide and 1 quantile for placebo (at Cavg of 0 nmol/L). The fitted solid line represents model-derived relations for each clinical program. The horizontal lines along the x axes represent medians and 90% exposure ranges, with the median exposure represented by a diamond. Data from SUSTAIN 1, 2, and 3; SUSTAIN-Japan; and PIONEER 1, 2, 3, 5, 8, and 9. The PIONEER and SUSTAIN populations differed somewhat with respect to demographic composition, and datasets were propensity matched. CI, confidence interval.

Overgaard 2021, Levels of circulating semaglutide determine reductions in HbA1c and body weight in people with type 2 diabetes

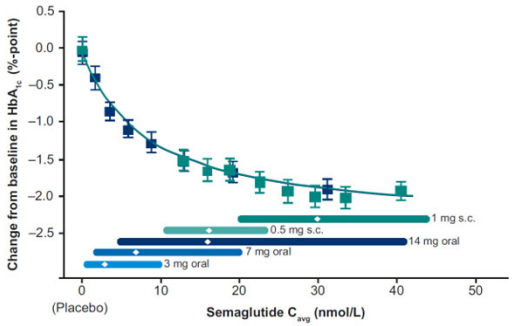


Fig. 5. Change from baseline in HbA1c in a propensity-score-matched population [94]. The plot shows the mean change and 95% CIs in HbA1c from baseline to Week 26 for the PIONEER program (including PIONEER 1, 2, 3, 5, 8, and 9) and Week 30 for the SUSTAIN program (SUSTAIN 1, 2, and 3; SUSTAIN-Japan). Exposure is presented as quantiles of Cavg for semaglutide and one quantile for placebo (at Cavg of 0 nmol/L). The fitted solid line represents modelderived relations for each program. The horizontal lines along the x-axes represent medians and 90% exposure ranges; median exposure is represented by a diamond. Datasets were propensity-matched due to differences in demographics between the PIONEER and SUSTAIN programs. Blue represents PIONEER, green represents SUSTAIN. Reprinted from: Overgaard et al. Cell Rep Med. 2021;2(9):100387. https:// doi. org/ 10. 1016/j. xcrm. 2021. 100387. Cavg average plasma concentration, CI confidence interval, HbA1c glycated hemoglobin, s.c. subcutaneous

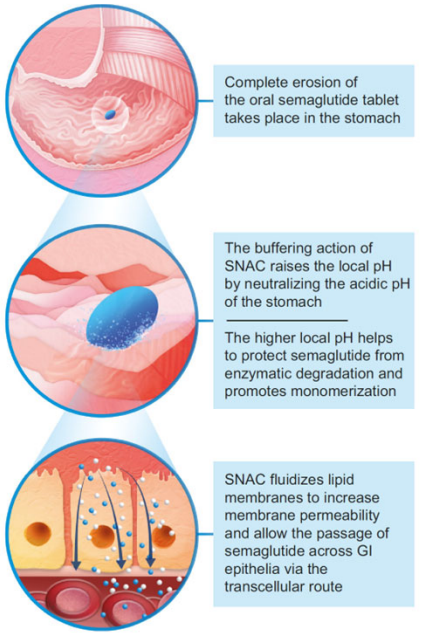


Fig. 2 Mechanism of absorption and protection of the semaglutide molecule [38, 56]. GI gastrointestinal, SNAC sodium N-(8-[2-hydroxybenzoyl]amino) caprylate

Findings from basic science and clinical research suggest that, in contrast to most oral drugs, semaglutide co-formulated with SNAC is absorbed in the stomach [56]. Scintigraphic imaging of human volunteers following a single dose of oral semaglutide (10 mg with 300 mg SNAC) demonstrated erosion of the tablet and absorption of semaglutide in the stomach [56]. In addition, plasma semaglutide levels were similar in dogs that had undergone pyloric ligation (to prevent intestinal absorption) compared with non-ligated dogs, and plasma concentrations in the splenic vein (draining the gastric cavity) were significantly higher than in the portal vein (draining the GI tract), further implicating the stomach as the site of absorption [56].

The absorption-enhancing action of SNAC is thought to be highly dependent on the specific agent it is enhancing, which means that carefully tailored co-formulation is required rather than co-administration [56]. The structure of liraglutide (a structurally distinct analog of GLP-1RA) was found to be unfavorable for co-formulation with SNAC on account of its stronger membrane-binding properties, which reduced transcellular passage, as well as its greater tendency to oligomerize, which countered the monomerizing effects of SNAC [56]. In a preclinical study, plasma exposure was significantly higher for semaglutide than liraglutide after oral dosing with SNAC [56].

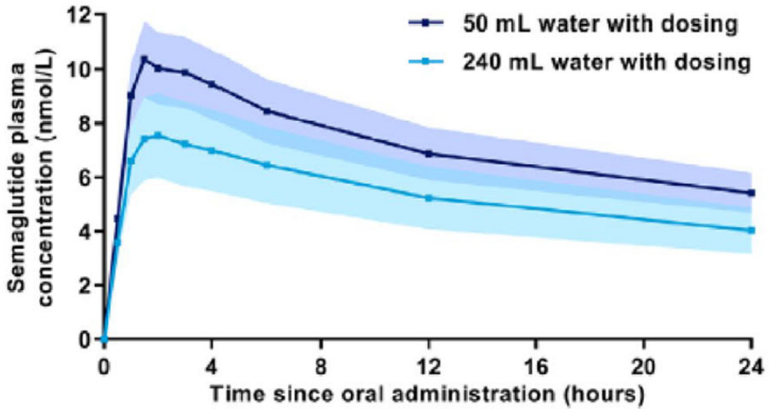
Aroda 2022, A new era for oral peptides: SNAC and the development of oral semaglutide for the treatment of type 2 diabetes

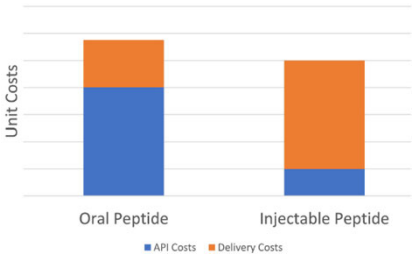
Oral Peptide Delivery System

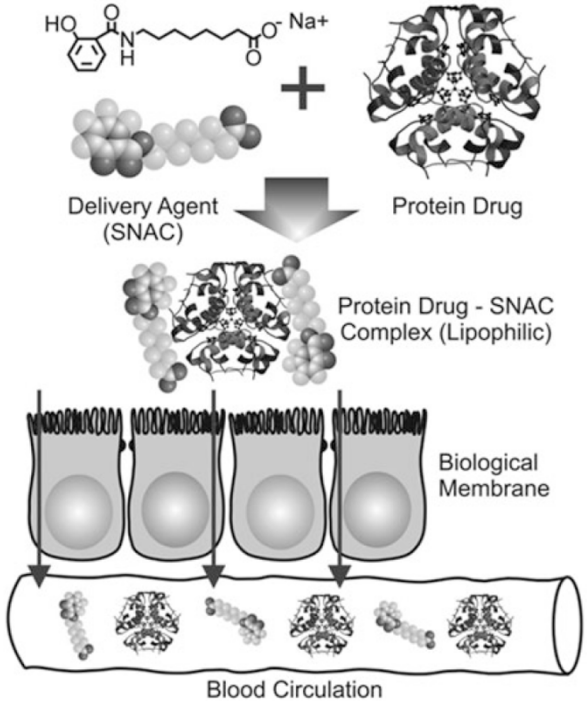
Rybelsus: building on 30 years of innovation

Understanding the mechanism of SNAC-enabled semaglutide absorption

Novo Nordisk selected Emisphere's Eligen technology—in particular the SNAC absorption enhancer—for further development, even so later buying some of Merrion's intellectual property in 2015 [13]. Emisphere had already clinically evaluated the site of absorption of an orally delivered peptide—evaluating their 4-CNAB absorption enhancer to enable to delivery of oral insulin, comparing the absorption when the payload was delivered either to the stomach or the small intestine. The results that showed an improved glucose lowering affect from an immediate release tablet which delivered the payload to the stomach compared to delivery direct to the small intestine, an early indication that this might be a potential site of absorption for an orally delivered peptide. This was a surprising finding as the prevailing dogma at the time was that oral peptides should target the small intestine [14].







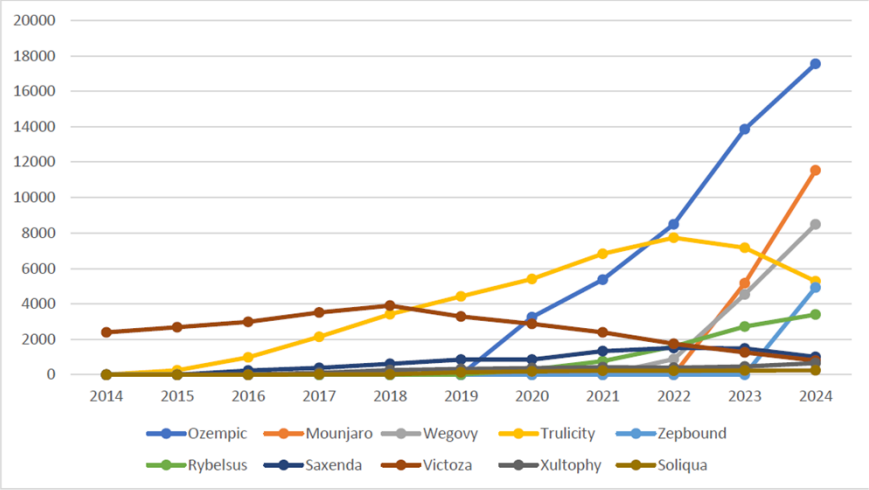
Lewis 2022, Development and approval of rybelsus (oral semaglutide)
Victor 2014, Eligen technology for oral delivery of proteins and peptides

Oral GLP-1 Delivery

Is there room for everyone at the GLP-1 table?
The role that generics and compound pharmacies are playing

By: Cindy H. Dubin. September 30, 2025
This has been a busy few months for all types of players in GLP-1 market. In Big Pharma, Eli Lilly announced Phase 3 results of an oral GLP-1 RA and Pfizer expands its GLP-1 portfolio by acquiring Metsera. In generics, Teva launched a generic liraglutide injection for weight loss. In the world of compounding pharmacies, Novo Nordisk ended its collaboration with Hims and Hers over "illegal mass compounding and deceptive marketing." This begs the question, what role are generics and compound pharmacies playing in the future GLP-1 space and is the $100 billion-plus market large enough for everyone?

Figure 1: Top 10 GLP-1 Drug Sales ($M), 2014-2024



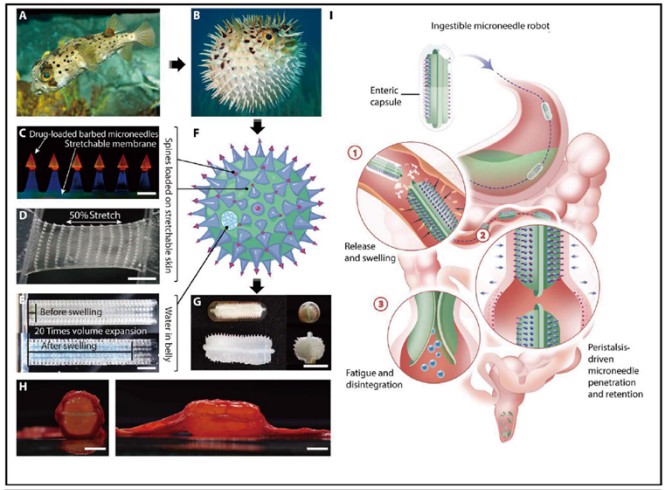
Source: PharmaCircle Key Product Sales

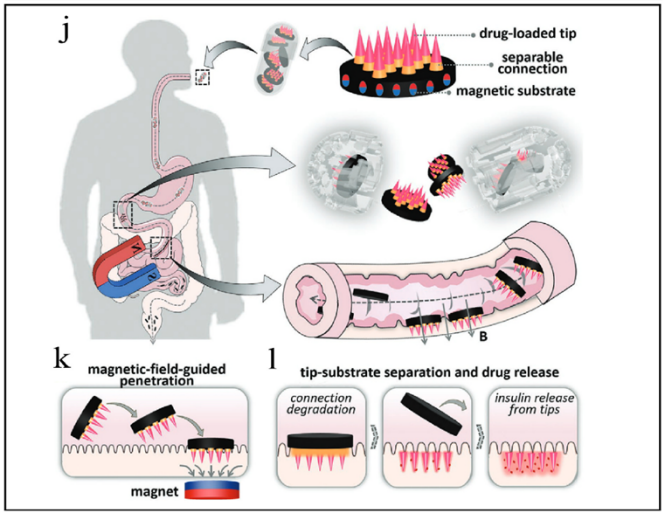
Compounding pharmacies fill a gap
Coming under scrutiny is the role compounding pharmacies are, and will be, playing in the GLP-1 space. While patients and health care professionals may look to unapproved versions of GLP-1 drugs, including semaglutide and tirzepatide, as an option for weight loss, this can be risky as unapproved versions do not undergo FDA's review for safety, effectiveness, and quality before they are marketed (FDA).
A Brookings Institution report highlights that many compounded semaglutide products rely on synthetic API imported from facilities in China that lack FDA oversight or quality controls. Alarmingly, 60% of Chinese manufacturers importing semaglutide for use in compounding or further manufacture are not even permitted to distribute that API in China for use in human drugs. According to FDA data, all semaglutide imported into the US designated for use in compounding since June 2023 originated from suppliers in China (Brookings Institution).
In April, the FDA clarified its policies regarding compounders as national GLP-1 supply began to stabilize. Part of the FD&C Act restricts compounded drugs that are "essentially copies of commercially available drugs," but certain amounts are permissible if the compounding is not done regularly or in inordinate amounts (FDA).

Dubin 2025, Is there room for everyone at the GLP-1 table

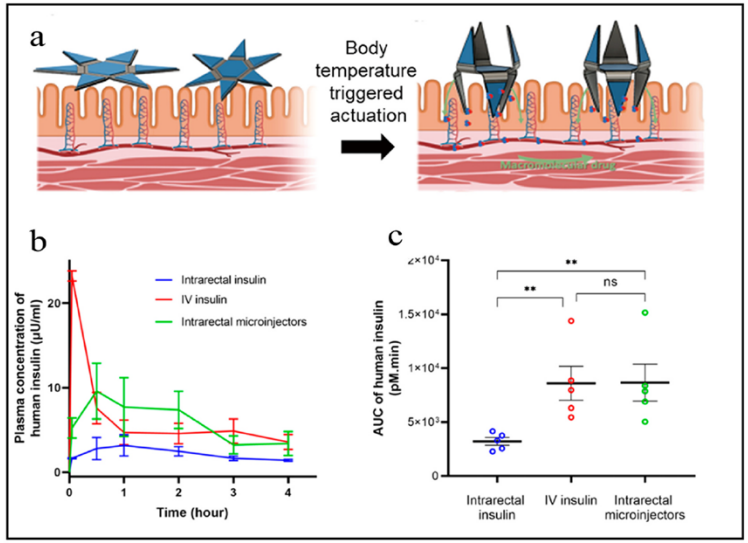
Oral Peptide Delivery

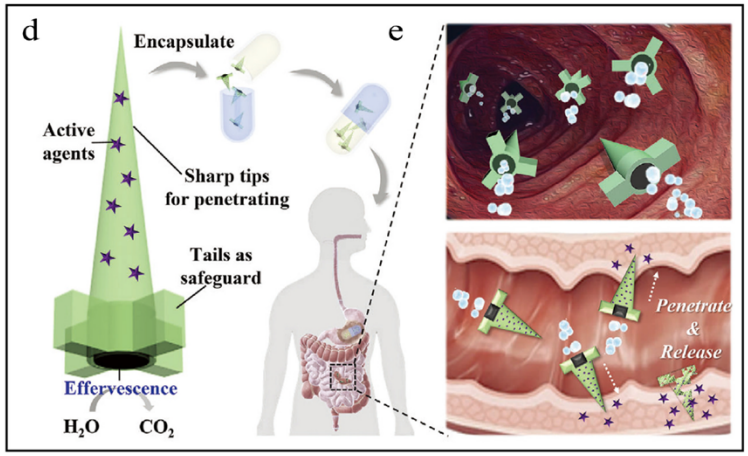
Oral Microneedle Systems





Stimulation-resposive oral microneedle Systems





Chen 2025, Supramolecular oral delivery technologies for polypeptide-based drugs

Transdermal Drug Delivery Systems

Transdermal Drug Delivery Systems

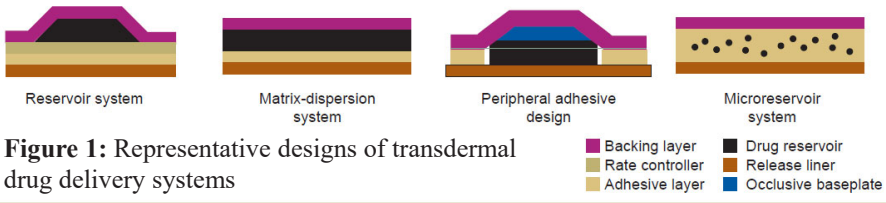


Figure 1: Representative designs of transdermal drug delivery systems

S. Kandavilli,V. Nair, and R. Panchagnula. Polymers in transdermal drug delivery systems. Pharm. Tech. May: 62-80, 2002

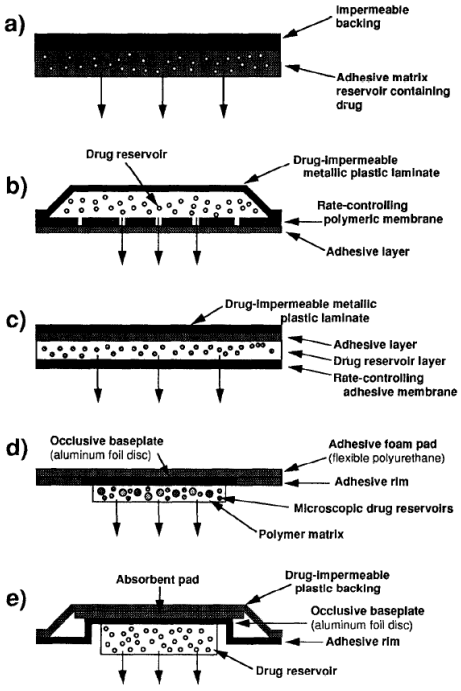


Fig. 1 Cross-sectional view of several TDS:
(a) pressure-sensitive adhesive (PSA) matrix device;
(b) membrane-moderated TDS;
(c) adhesive-controlled TDS;
(d) microreservoir-type TDS;
(e) matrix dispersion-type TDS.

K. Sugibayashi and Y. Morimoto. Polymers for transdermal drug delivery systems. J. Control. Release 29 (1994) 177-185.

PLGA Nanofibers for Transdermal Delivery

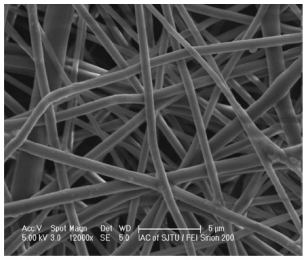


Fig. 3. SEM morphology of Daidzein-NLCs-Azone-nanofibers.

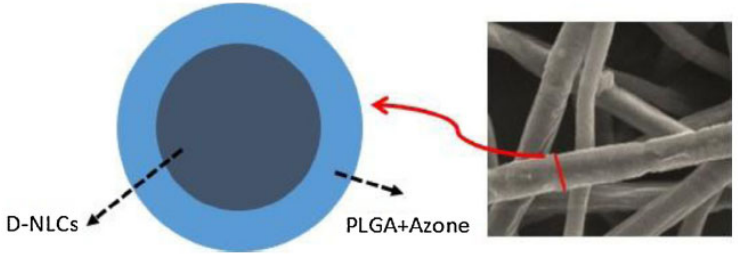


Fig. 4. Schematic figure of cross-sectional view of D-NLCs-Azone-nanofibers.

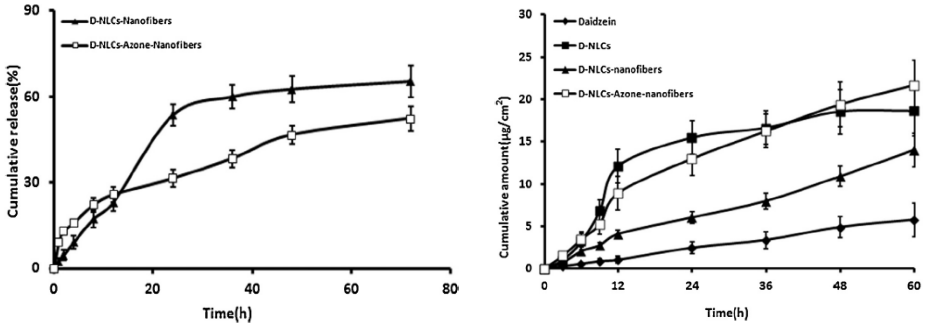
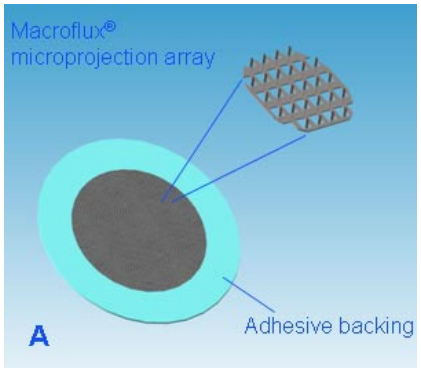
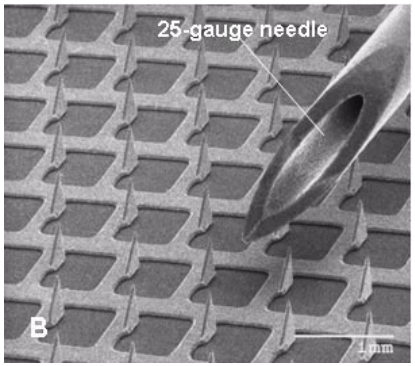


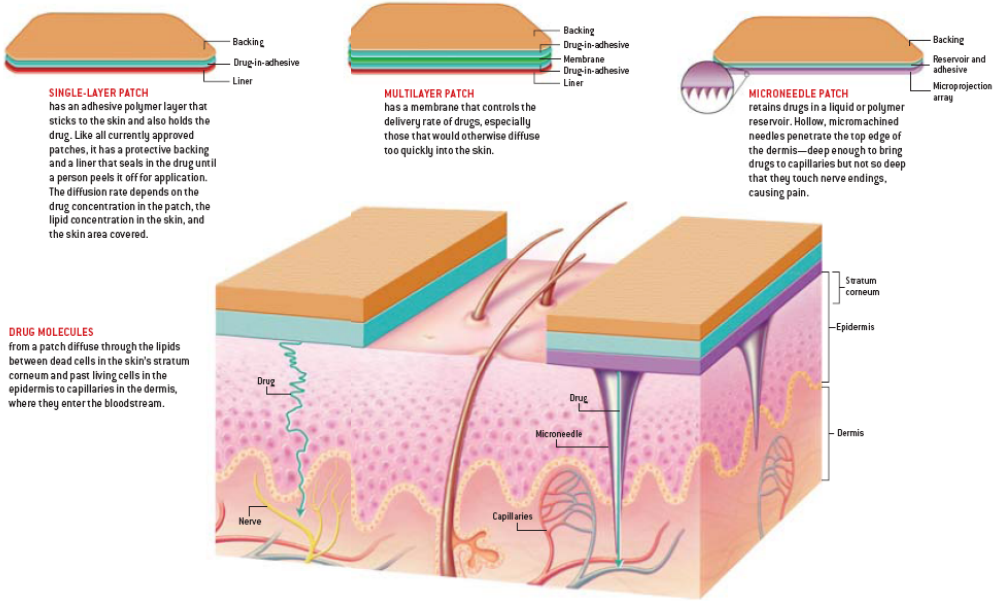
Fig. 5. In vitro release profile of daidzein from D-NLCs-Nanofibers and D-NLCs- Azone-Nanofibers in Phosphate Buffered Saline (pH 7.4). Keys: (▲) D-NLCs- Nanofibers, (□) D-NLCs-Azone-Nanofibers. Each value represents the mean±SD (n = 3).

J. Song, X. Fan, Q. Shen. Daidzein-loaded nanostructured lipid carriers-PLGA nanofibers for transdermal delivery. International Journal of Pharmaceutics 501 (2016) 245-252.

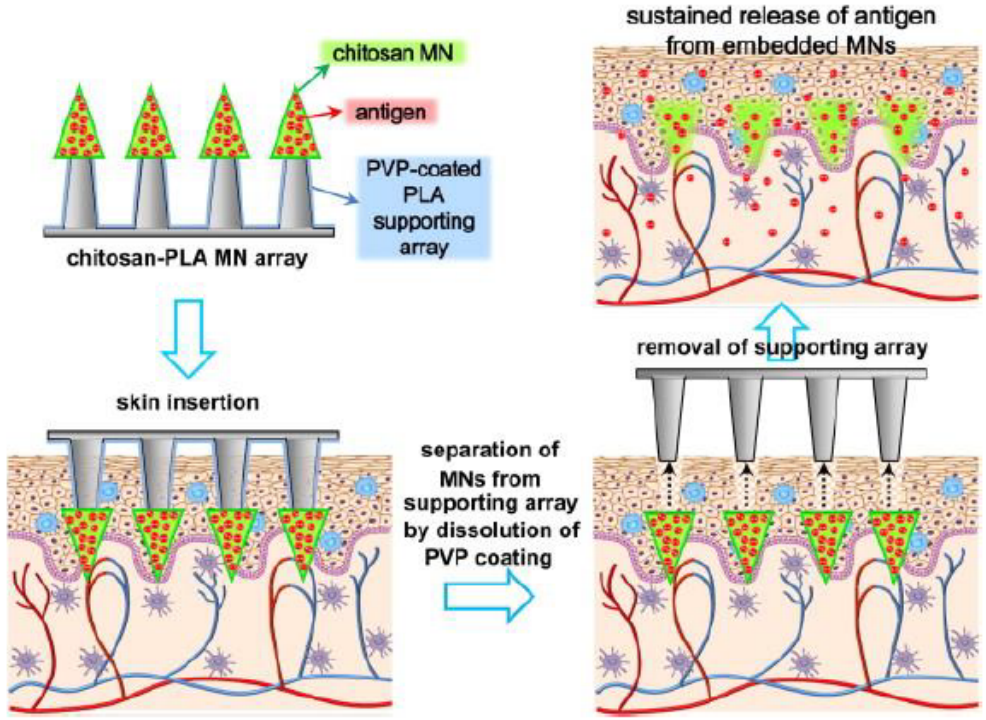
Transdermal Patches with Microneedles







Scientific American. April 2003



Chen, M.-C., Huang, S.-F., Lai, K.-Y., Ling, M.-H.: Fully embeddable chitosan microneedles as a sustained release depot for intradermal vaccination. Biomaterials 34(12): 3077-3086, 2013.

Microneedle Transdermal Drug Delivery

Phase-Transition Microneedle Patches

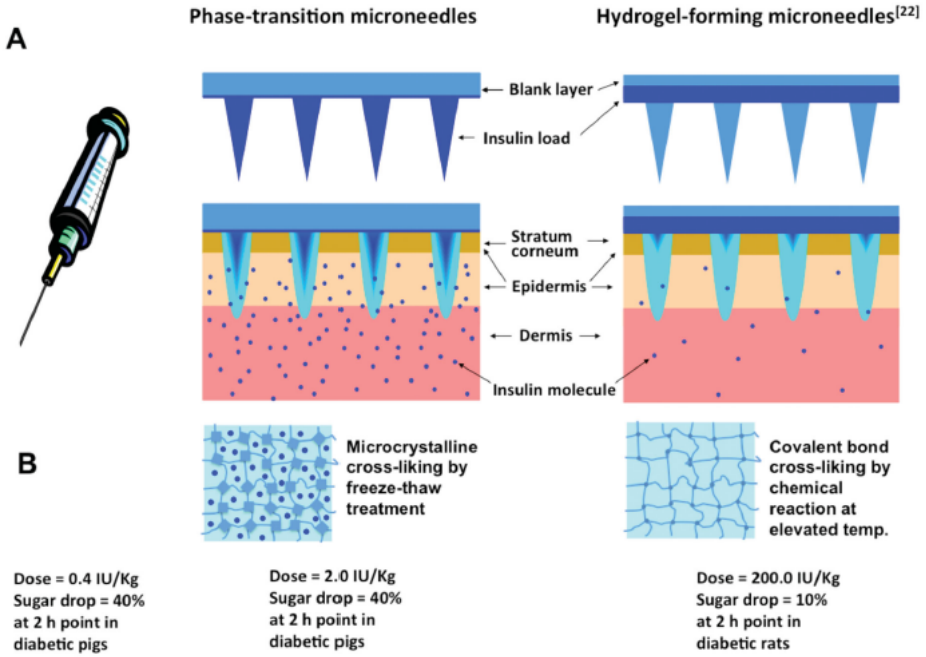


Figure 1. Working principle and fabrication process of PTM patches.
A) The microneedles absorb the bodily fluid from the dermis layer to convert form hard glassy state to hydrogel state to allow the preloaded insulin to release to the bodily fluid in the dermis layer.
B) The microneedle matrix of PTM is cross-linked to avoid dissolution through microcrystalline domains as the cross-linking junctions via a freeze-thaw treatment while that of HFM is cross-linked through covalent bands as the cross-linking junctions via a chemical reaction. Therefore, insulin can be loaded in the needle tips of PTM to achieve a relative bioavailability of 20%, while insulin has to be loaded at the back of the microneedle array of HFMs that leads to a bioavailability less than 1% due to the extended diffusion pathway.

Sixing Yang, Fei Wu, Jianguo Liu, Guorong Fan, William Welsh, Hua Zhu, Tuo Jin:
Phase-Transition Microneedle Patches for Efficient and Accurate Transdermal Delivery of Insulin.
Adv. Funct. Mater. 25 (29): 4633-4641, 2015.

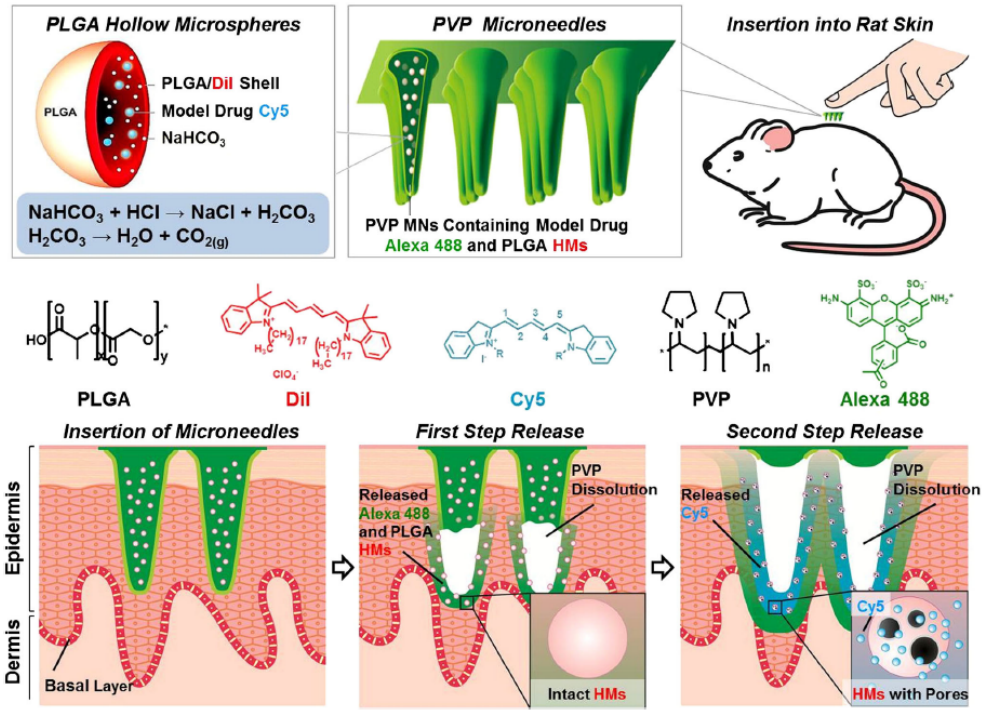


Fig. 2 Schematic illustration of the design of PVP MN arrays containing pH-responsive PLGA HMs and their mechanism for codelivery of two different model drugs Alexa 488 and Cy5 in sequence transdermally. After insertion into skin, the first step of rapid release of Alexa 488 and DiI-labeled HMs was accomplished due to quick

Naves 2017, Poly(lactic-co-glycolic) acid drug delivery systems through transdermal pathway: an overview. Prog. Biomater. 6:1-11, 2017.

Polymeric Microneedles for Transdermal Protein Delivery

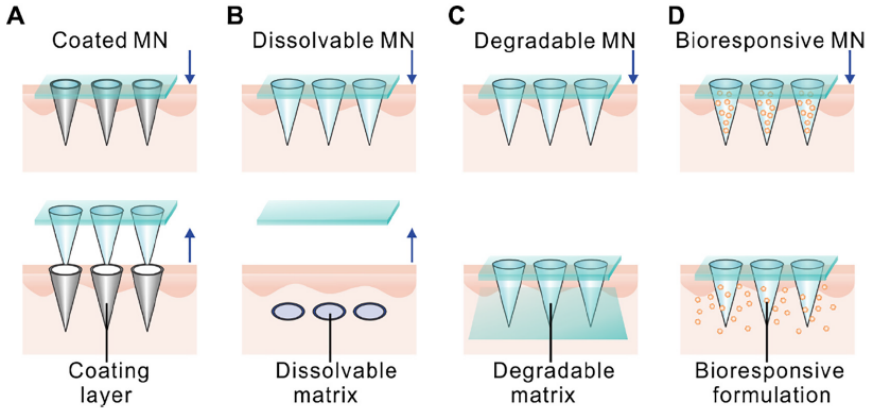
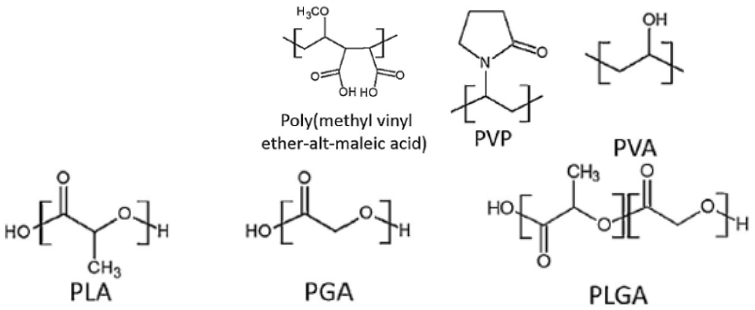


Fig. 1. Representative types of polymeric MNs for protein delivery. A) Solid MNs coated with polymeric drug formulation on the MNs surface for direct delivery. B) Dissolvable polymeric MNs that remain in the skin and dissolve to deliver the drug encapsulated within. C) Degradable polymeric MNs that remain in the skin and degrade over time. Drug delivery occurs via passive diffusion or degradation of the polymeric matrix. D) Bioresponsive polymeric MNs. Drug release is dependent on the degradation or dissociation of MN matrix and/or formulations from the MN matrix.

Y. Ye, J. Yu, D. Wen, A.R. Kahkoska, Z. Gu. Polymeric microneedles for transdermal protein delivery. Advanced Drug Delivery Reviews 127 (2018) 106-118.



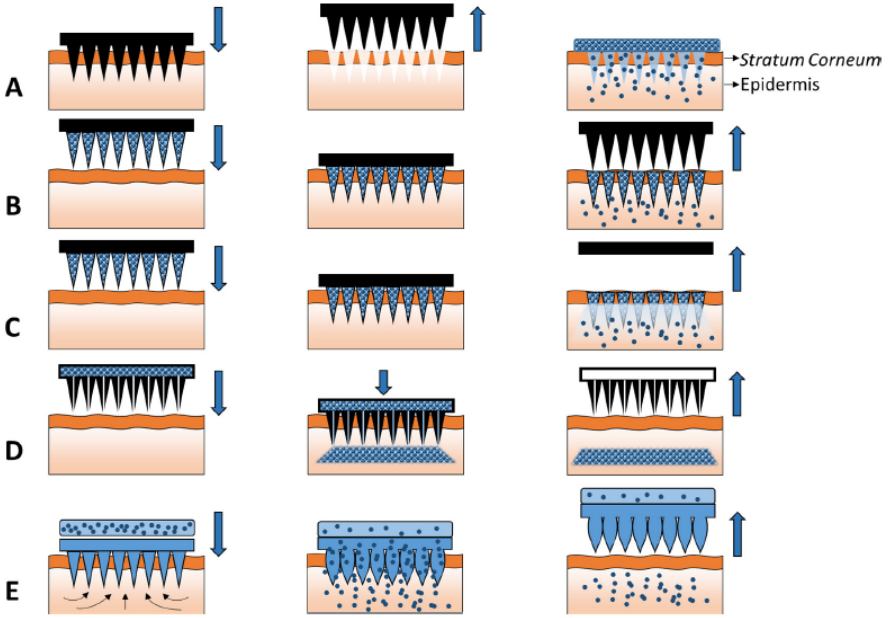


Fig. 1. A schematic representation of five different MN types used to facilitate drug delivery transdermally. (A) Solid MNs for increasing the permeability of a drug formulation by creating micro-holes across the skin. (B) Coated MNs for rapid dissolution of the coated drug into the skin. (C) Dissolvable MNs for rapid or controlled release of the drug incorporated within the microneedles. (D) Hollow MNs used to puncture the skin and enable release of a liquid drug following active infusion or diffusion of the formulation through the needle bores. (E) Hydrogel forming MNs take up interstitial fluids from the tissue, inducing diffusion of the drug located in a patch through the swollen microprojections.

Larraneta 2016, Microneedle arrays as transdermal and intradermal drug delivery systems: Materials science, manufacture and commercial development. Mater. Sci. Eng. R 104 (2016) 1-32

Poly(lactic-co-glycolic acid) Gradient Porous Microneedle Array

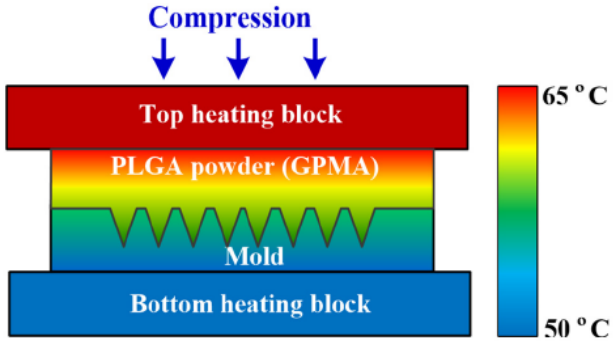
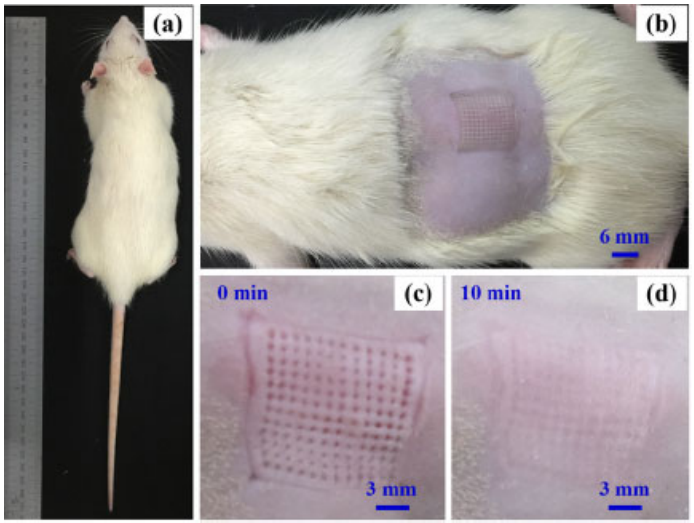


Fig. 1. Schematic of modified hot embossing setup for the GMPA fabrication.



J. Li, Y. Zhou, J. Yang, R. Ye, J. Gao, L. Ren, B. Liu, L. Liang, L. Jiang. Fabrication of gradient porous microneedle array by modified hot embossing for transdermal drug delivery. Materials Science and Engineering: C 96 (2019) 576-582

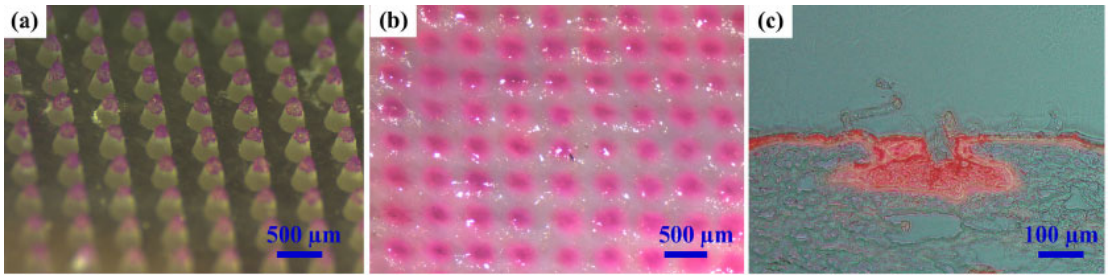


Fig. 6. (a) GPMA loaded with dried Rhodamine B at microneedle tips, (b) rabbit skin punctured by GPMA, and (c) drug diffusion image of punctured skin slice.

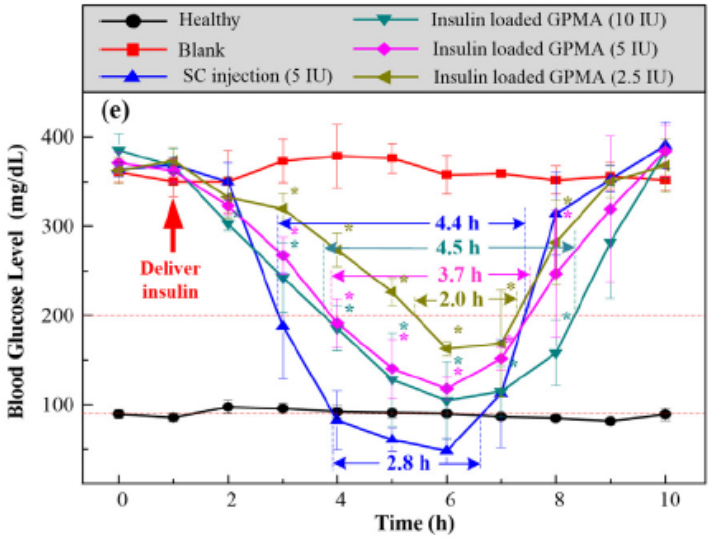
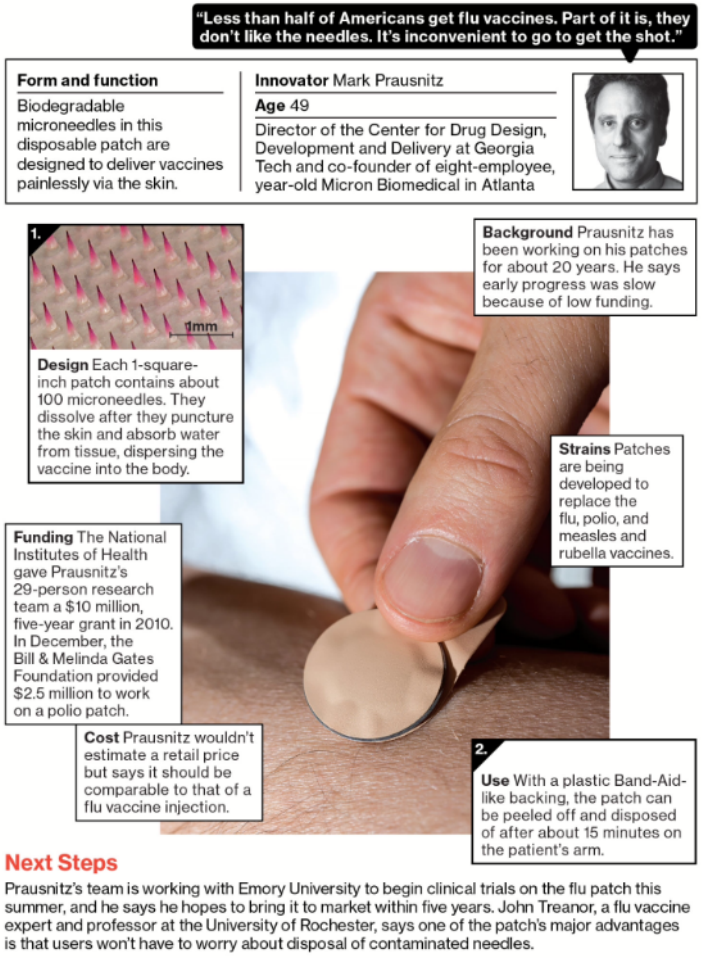


Fig. 7. Transdermal insulin delivery in diabetic rats: (a) diabetic SD rats with a weight of approximately 200 ± 20 g were selected, (b) SD rat treated with GPMA patch, (c-d) skin recovery process after removing the GPMA, and (e) BGLs in diabetic rats after transdermal administration of insulin-loaded GPMA and SC injection (n=5).

Transdermal Vaccine Patches

Vaccine Patch: Vaccination without needles, the best idea ever
By Caroline Winter. Bloomberg Businessweek. May 18, 2015



Medicinal Patches

At China's Chengdu University of Traditional Chinese Medicine hospital, twin sisters Zheng Yue and Zheng Hao wear medicinal patches that contain a formula of herbal medicine used as a seasonal treatment to expel heat from the body during summer. Photograph by Fritz Hoffmann. Nat Geo 2019: A Year in Review

Drug Delivery: Future

The Use of Artificial Intelligence to Support Regulatory Decision-Making

Considerations for the Use of Artificial Intelligence to Support Regulatory Decision-Making for Drug and Biological Products
Guidance for Industry and Other Interested Parties

AI/Machine Learning in Drug Delivery Systems

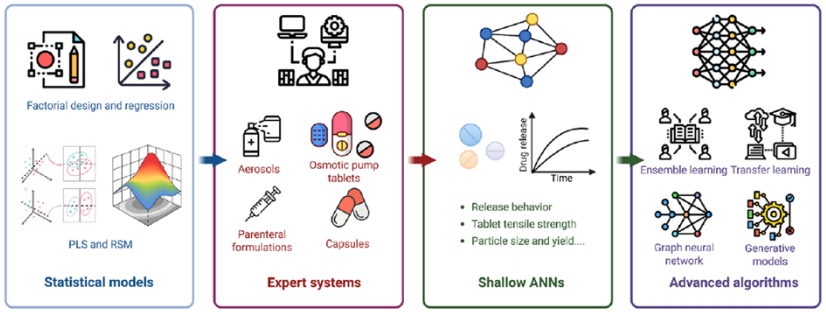


Figure 2. Evolution of computational methods in drug delivery.

Table 2 Early representative computational applications in drug delivery.

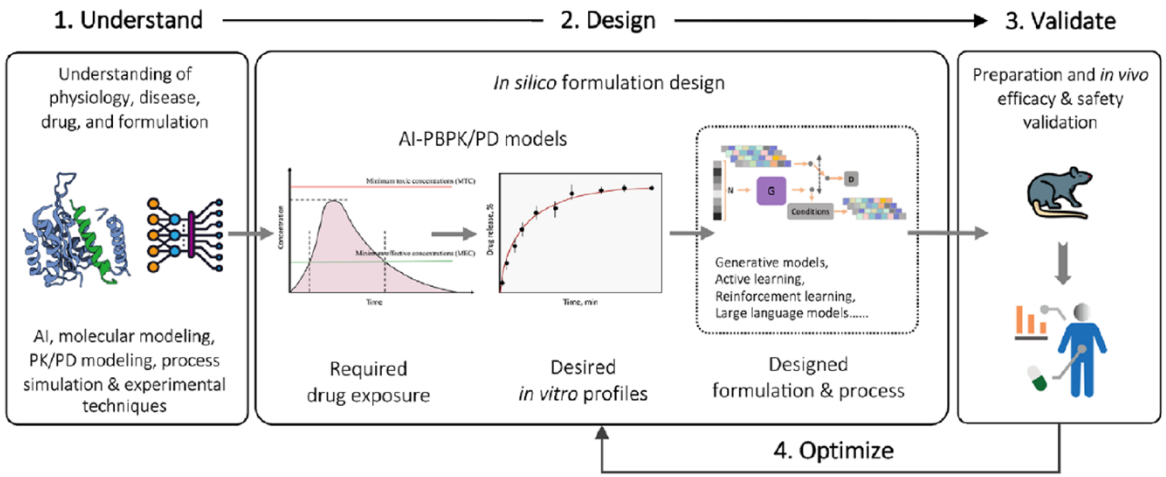
Year	Computational method	Dosage form	Dataset	Objective	Ref.
1973	Factorial design	Tablet	27 data (1 API and 1 excipient)	Predict disintegration time, tablet hardness, friability, weight, thickness, porosity, mean pore diameter, and dissolution (% at 30min).	20
1990	Expert system	Aerosols, capsules, granulates, injection solutions, and tablets	Not mentioned	Carrying out 'theoretical experiments' by the computer using galenical knowledge before testing drug products in practical experiments	21
1991	RSM and ANN	Matrix capsule	23 data (1 API and 4 excipients)	Predict release exponent N and the dissolution half-time $T_{0.5}$	22
1998	ANN	Sustained-release matrix tablets	3 data (1 API and 1 excipient)	Establish *in vitro–in vivo* correlation (IVIVC)	23
2000	ANN	Osmotic pump tablets	30 data (1 API and 2 excipients)	The drug release rate and the correlation coefficient	24
2002	MLR and PLS	Pure drug	17 data (17 drugs)	Predict intrinsic solubility	25
2003	PLS	Pure drug	23 data (23 drugs)	Predict solubility and permeability	26
2006	Neurofuzzy logic and neural networks	Immediate-release tablet	205 data (1 API and 4 excipients)	Predict tablet tensile strength, disintegration time, friability, capping, and drug dissolution rate (%) at 15, 30, 45, and 60 min.	27
2011	Expert system	Osmotic pump tablets	Hundreds of PPOP data	Establish a formulation design model based on the prediction of release behavior	28
2014	RSM and ANN	Solid dispersions	46 data (6 APIs and 1 excipient)	Predict yield, outlet temperature, and mean particle size	29
2015	RSM and ANN	Nanoparticles	18 data (1 API and 4 excipients)	Predict particle size and loading efficiency	30

API, active pharmaceutical ingredient; ANN, artificial neural network; RSM, response surface methodology; MLR, multilinear regression; PLS, partial least square; PPOP, push–pull osmotic pump tablets.

Table 3 Comparison of early and current AI applications in drug delivery.

Aspect	Early AI	Current AI
Data volume	Smaller datasets (typically <100 data samples)	Larger datasets (typically ≥500 data samples)
Formulation scope	Limited to a few drugs and excipients	≥ 10 drugs and all important excipients
Data representation	Simple representation of drugs and excipients (*e.g.*, basic molecular descriptors)	Advanced molecular representations, including molecular descriptors, molecular fingerprints, 3D conformations, molecular graphs, and text-based embeddings
Algorithms	Basic statistical methods, expert systems, and simple neural networks	Advanced AI algorithms, including classic machine learning (*e.g.*, LightGBM), deep neural networks, and advanced architectures such as transformers and generative models
Generalization	Poor generalization, formulation optimization	Better generalization, formulation, and prediction
Interpretability	Limited interpretability for neural networks	Advanced algorithms and tools for model interpretability
Computational resources	Restricted by limited computational power and infrastructure	Supported by cloud computing and high-performance GPUs

3D, three dimension; AI, artificial intelligence; GPUs, graphics processing units.



Wu 2025, Artificial intelligence for drug delivery- Yesterday, today and tomorrow

AI/Machine Learning in Drug Delivery Systems

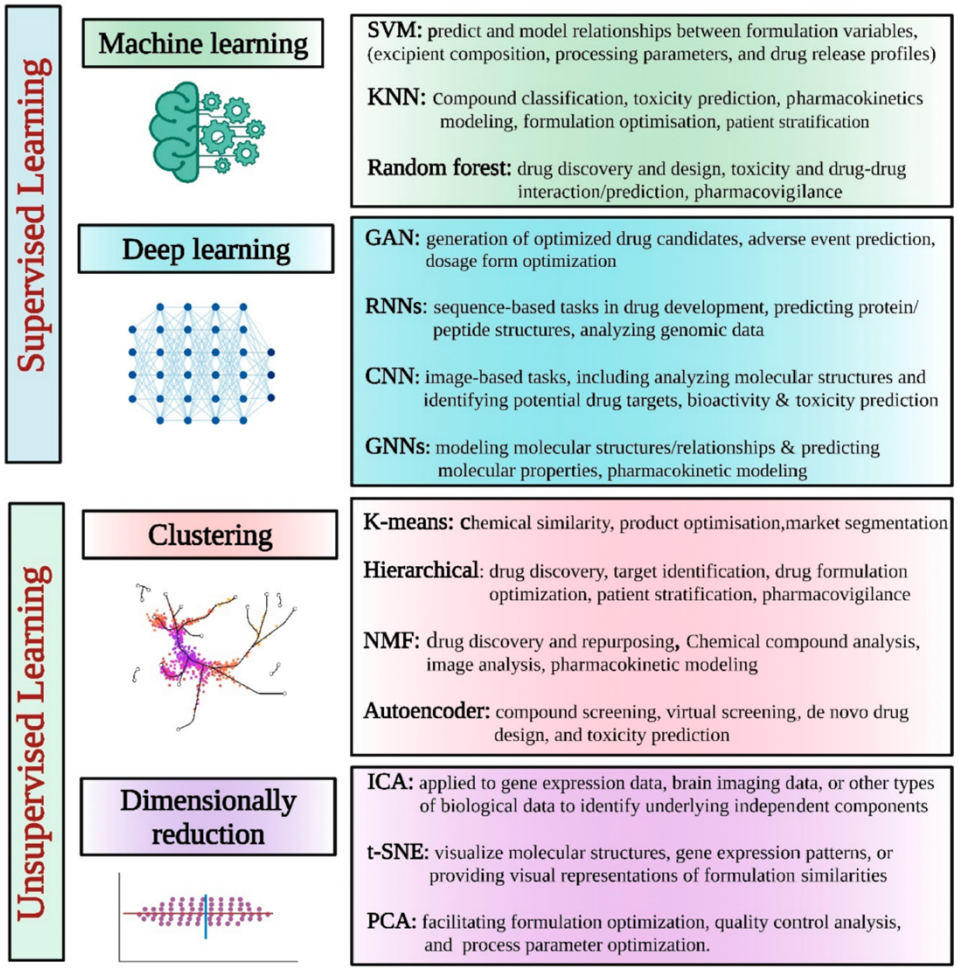


Figure 2. Different supervised and unsupervised AI learning models/tools for pharmaceutical applications.

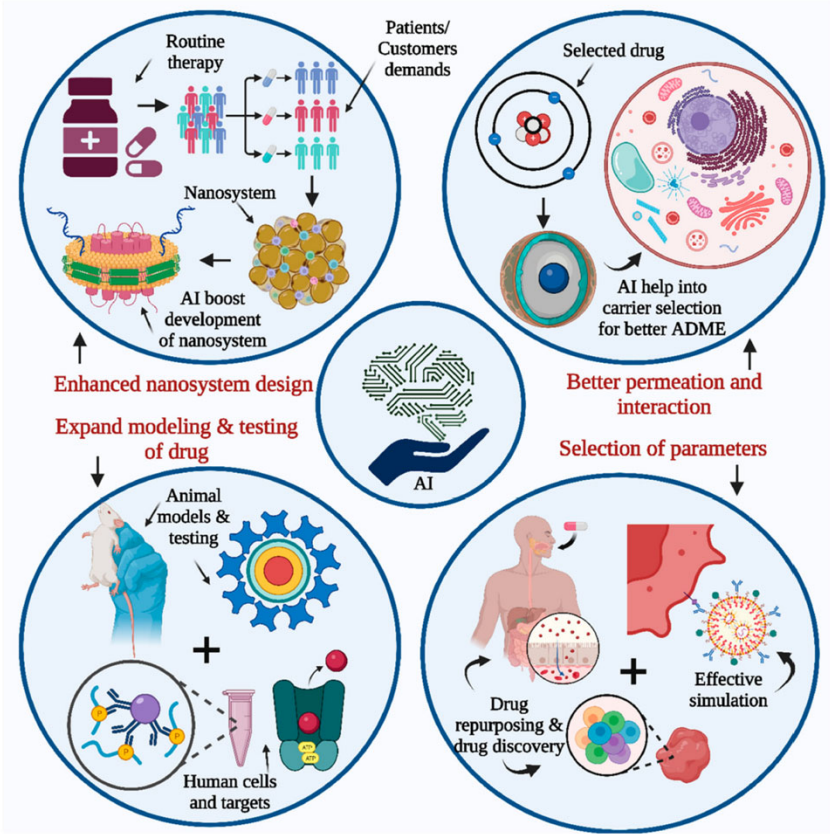


Figure 3. AI contribution to drug development and research. AI can be used to enhance nanosystem design, expand the present drug testing modeling system, and increase the accuracy of parameter and factor selection in drug design, drug discovery, and drug repurposing methods. It also helps to better understand the mechanism of membrane interaction with the modeled human environment by studying drug permeation, simulation, human cell targets, etc.

Vora 2023, Artificial intelligence in pharmaceutical technology and drug delivery design

AI/Machine Learning in Drug Delivery Systems

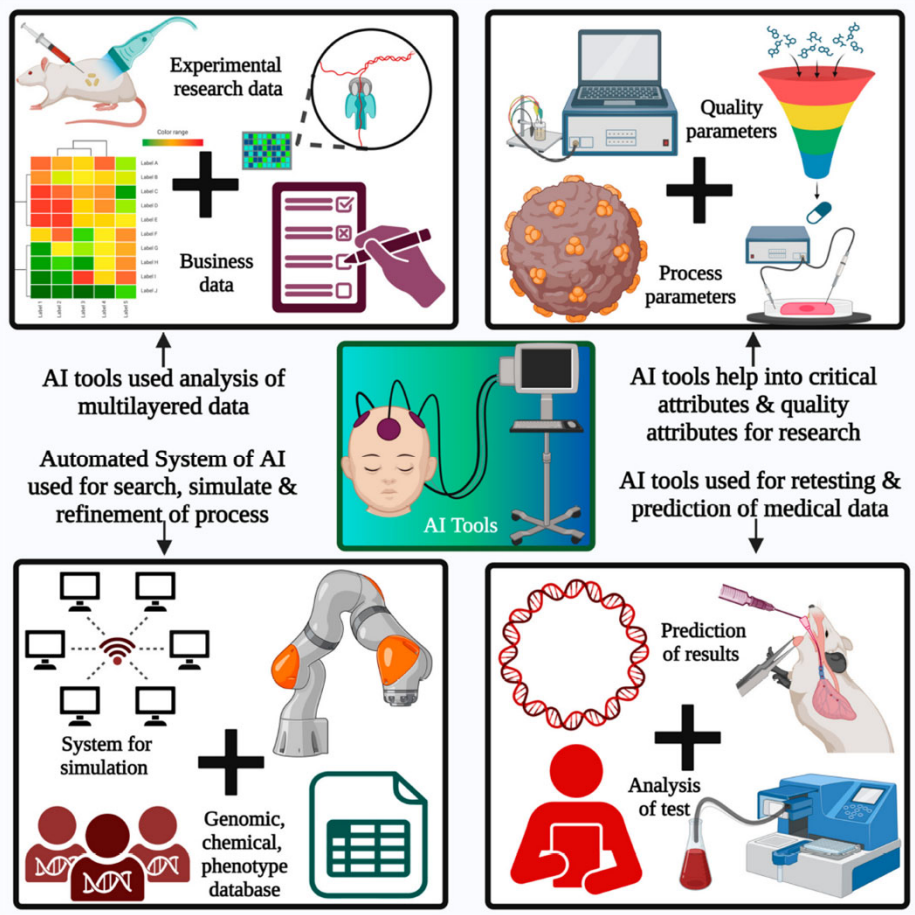


Figure 4. Application of AI tools in the pharma sector. AI tools are helpful for the analysis of multilayered data. Automated AI systems are used to perform effective searches, simulations, and refinements of data and processes involved in research and product development. The system biology database, chemical database, genomic database, phenotypic database, and AI bots are used for better exploration of drug models, drug release, and activity predictions along with recommendations for effective drug delivery systems.

Vora 2023, Artificial intelligence in pharmaceutical technology and drug delivery design

Machine Learning Models for Polymeric Long-acting Injectables

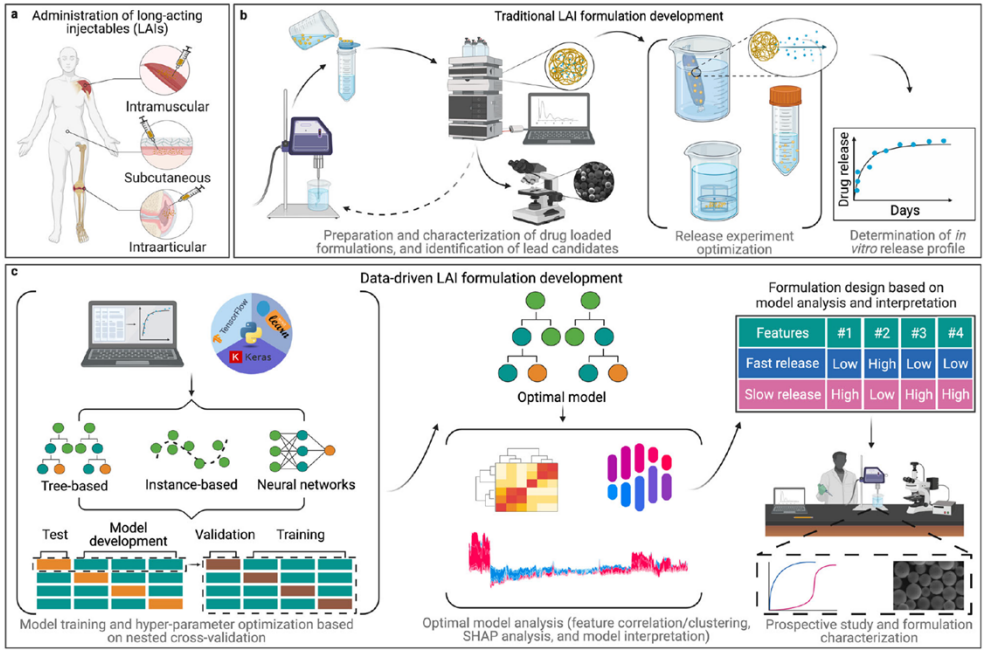


Fig. 1. Schematic demonstrating traditional and data-driven formulation development approaches for long-acting injectables (LAIs). **a** Selected routes of administration for FDA-approved LAI formulations. **b** Typical trial-and-error loop commonly employed during the development of LAIs termed "traditional LAI formulation development". **c** Workflow employed in this study to train and analyze machine learning (ML)models to accelerate the design of new LAI systems, termed "Data-driven LAI formulation development".

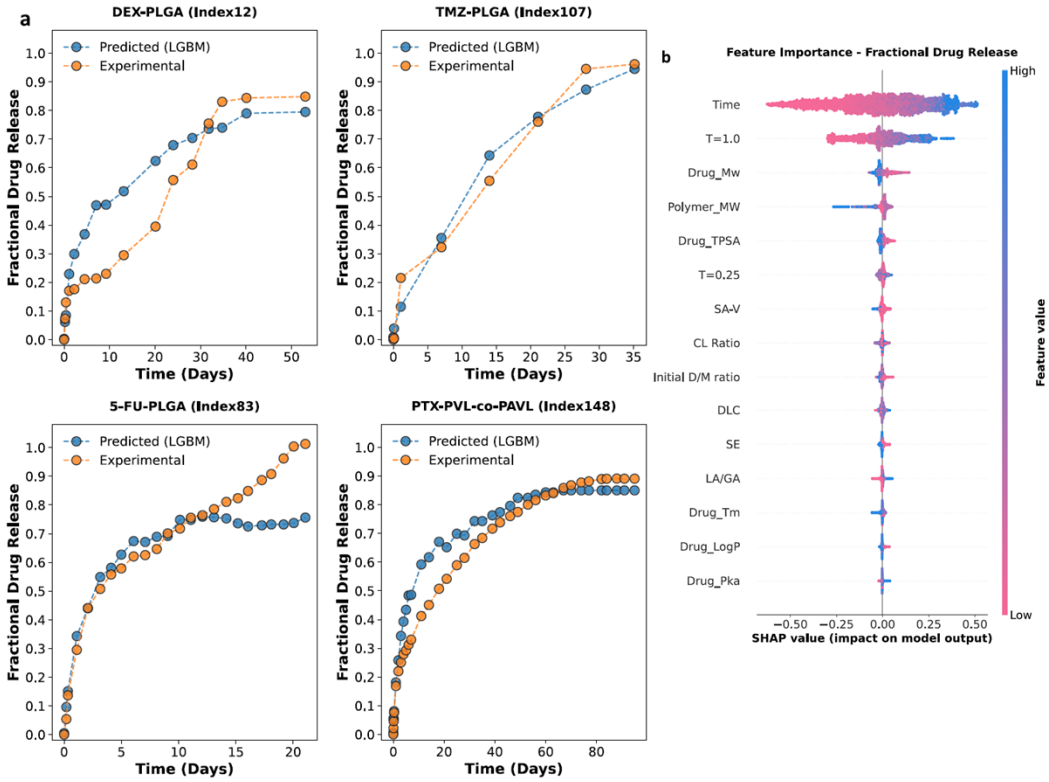


Fig. 4 | Deployment of the trained 15-feature lightGBM (LGBM) model. a Select examples of experimental fractional drug release profiles (orange circles) in comparison to predicted fractional drug release profiles (blue circles) generated by the LGBM model. These include dexamethasone-loaded PLGA MPs (DEX-PLGA); temozolomide-loaded PLGA MPs (TMZ-PLGA); fluorouracil-loaded PLGA MPs (5-FU-PLGA); and paclitaxel-loaded PVL-co-PAVL cross-linked cylinders. b Shapley additive explanations (SHAP) analysis for the 15-featureLGBMmodel. The impact of each feature on fractional drug release is illustrated through a swarm plot of their corresponding SHAP values. The color of the dot represents the relative value of the feature in the dataset (high-to-low depicted as pink-to-blue). The horizontal location of the dots shows whether the effect of that feature value contributed positively or negatively in that prediction instance (x-axis

Bannigan 2023, Machine learning models to accelerate the design of polymeric long-acting injectables

Machine Learning Models for Polymeric Long-acting Injectables

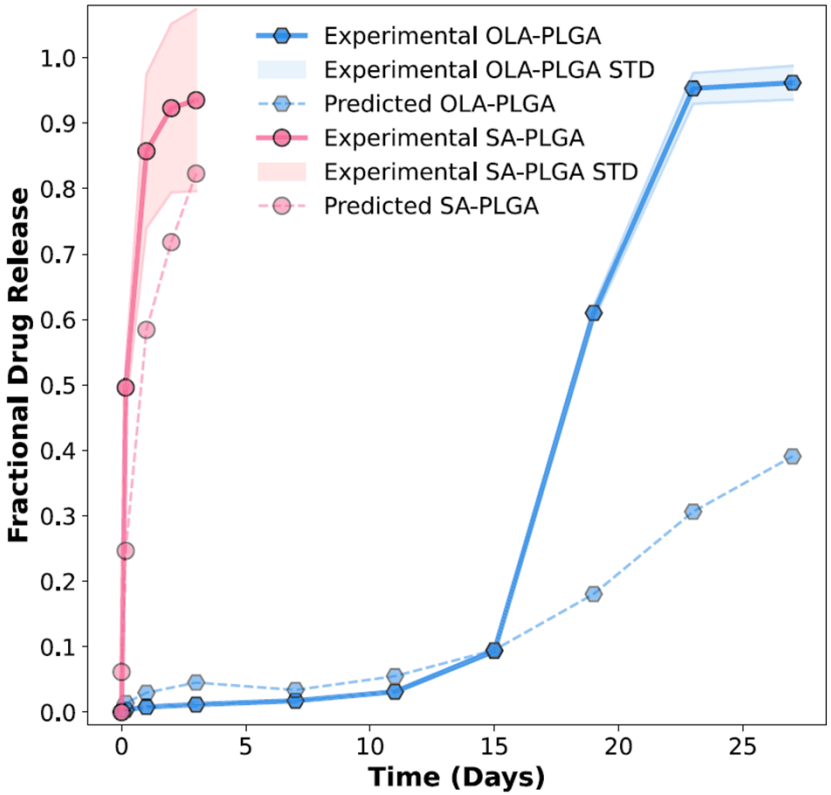


Fig. 7 | Comparison of the experimental and predicted fractional drug release profiles for the salicylic acid-PLGAMP (SA-PLGA) and olaparib-PLGA MICROPARTICLE (OLAPLGA) formulations. The design of both the SA-PLGA and OLA-PLGA was based on SHAP analysis of the trained LGBM model. Three independent batches of both formulations wereprepared, and their experimental drug release was characterized in 0.5wt% sodium dodecyl sulfate (SDS) to ensure sink conditions throughout the experiments. The fractional experimental drug release profiles for SA-PLGA and OLA-PLGA are plotted together as pink circles with a solid line (SA-PLGA) and blue hexagons with a solid line (OLA-PLGA), respectively. In both cases, the standard deviation (STD) observed for these experimental drug release measurements is displayed as a colored halo (n = 3). The fractional drug release profiles predicted by the LGBM model are also shown as pale pink circles with a broken line (SA-PLGA) and pale blue hexagons with a broken line (OLA-PLGA), respectively.

Bannigan 2023, Machine learning models to accelerate the design of polymeric long-acting injectables

AI/Machine Learning in Drug Delivery Systems

2.2.2. Machine learning modeling

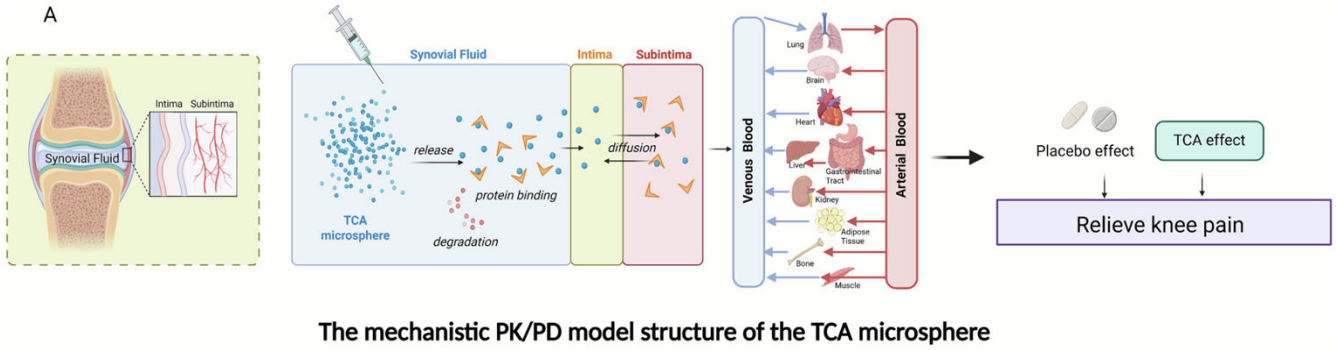
2.2.2.1. Data collection. The dataset of ISFG formulations was constructed using both published data [56–86]. It includes a total of 196 PLGA-based ISFG formulations for 37 small-molecule drugs, with data spanning 2500 time points. The release data were extracted from *in vitro* release profile figures. Several criteria were applied during the screening process: only formulations containing three components: API, polymer PLGA, and solvent were included. Formulations with combination drugs, multiple polymers in varying proportions, or several different solvents were excluded. Triblock copolymers (PLGA-PEG-PLGA and PEG-PLGA-PEG) were not included in this dataset. Combination delivery systems, where microspheres were used as the first-level drug carrier and *in situ* gel as the second-level carrier, were also excluded.

Table 3 outlines the features employed in prediction models for various formulations. The total 46 input features are categorized according to their relevance to different components involved in the formulation and dissolution process: API, PLGA, solvents, and *in vitro* dissolution parameters (see Supplementary Fig. S1 for data distribution of key features). API, solvent, and surfactants (in dissolution medium) features were encoded as molecular descriptors and subsequently sourced from chemical databases. These API features characterize the physical and chemical properties of the API. For polymers, the features considered include the lactic acid/glycolic acid molar ratio (LA/GA molar ratio), molecular weight (Mw), endgroup, intrinsic viscosity, and concentration. These parameters describe the polymer's composition and physical characteristics, which can influence drug release. Solvent-related features were selected to characterize the solvent's ability to dissolve the API and its interaction with other formulation components. Additionally, experimental-condition variables (*e.g.*, dissolution medium pH, dissolution medium concentration, temperature, rotate speed, dissolution medium volume, surfactant presence and concentration) were included as model inputs to account for methodological heterogeneity among literature sources. Release data were normalized by time to ensure cross-study comparability. Surfactant-related descriptors (*e.g.*, Sur_flash point, Sur_logP, Sur_HLB *etc.*) were derived from the dissolution medium, as medium composition and surfactant properties can substantially affect solvent exchange and apparent dissolution behavior of ISFGs. Although not all literature studies used surfactant-containing medium, inclusion of surfactant descriptors in the feature set allowed the ML model to account for these methodological variations and maintain prediction reliability across different release conditions. The fractional drug release within the first 24 h was also included as an input feature, given the consistent observation of an initial burst release within this period [52]. The PLGA end group and dissolution methods were deemed as multi-categorical variables. The output variable was the cumulative drug release at various time points.

Table 3
Features applied in prediction models.

Formulation	Input features
API	API_concentration(%*w*/w), API_Mw(g/mol), API_HBDC, API_HBAC, API_RBC, API_TPSA, API_HAC, API_complexity, API_melting_point, API_logS, API_logP
Polymer	LA/GA_molar_ratio, PLGA_concentration(%w/w), PLGA_Mw(kDa), PLGA_endgroup, PLGA_intrinsic_viscosity (dl/g)
Solvent	Sol_XLogP3, Sol_TPSA, Sol_complexity, Sol_electric_constant, Sol_viscosity(mPa.s), Sol_Mw, Sol_logP, Sol_boiling_point, Sol_melting_point, Sol_density, Sol_flash_point, Sol_vapor_pressure
***In vitro* dissolution condition**	Needle, dissolution_medium_concentration(mM), surfactant_concentration(%*w*/*v*), Sur_Mw, Sur_logP, Sur_melting_point, Sur_density, Sur_flash_point, Sur_surface_tension, Sur_HLB, dissolution_pH, dissolution_temperature, dissolution_rotate_speed(rpm), dissolution_media_volume(ml)
Others	Release_day1

Mw: molecular weight; HBDC: hydrogen bond donor count; HBAC: hydrogen bond acceptor count; RBC: rotatable bond count; TPSA: topological polar surface area; HAC: heavy atom count; HLB: hydrophile- lipophile balance; Sol: solvent; Sur: surfactant in dissolution medium.



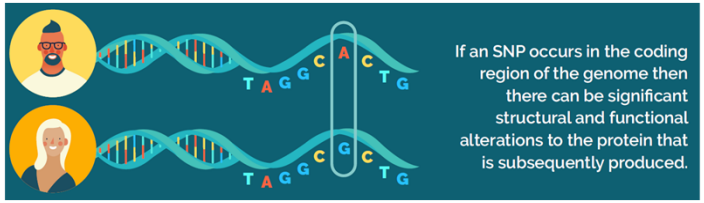
The mechanistic PK/PD model structure of the TCA microsphere

Xiong 2026, FormulationLAI- A physiology-based machine learning framework for accelerated development of long-acting injectable formulations

Precision Medicine

Pharmacogenetics

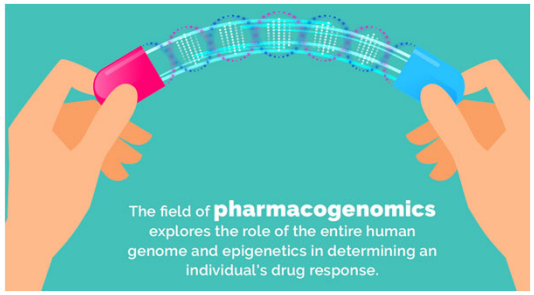
The study of genetic factors (heredity) that influence response to drugs and the predisposition to develop adverse effects.
The correlation of the DNA sequence of genes to a drug response.



Pharmacogenomics

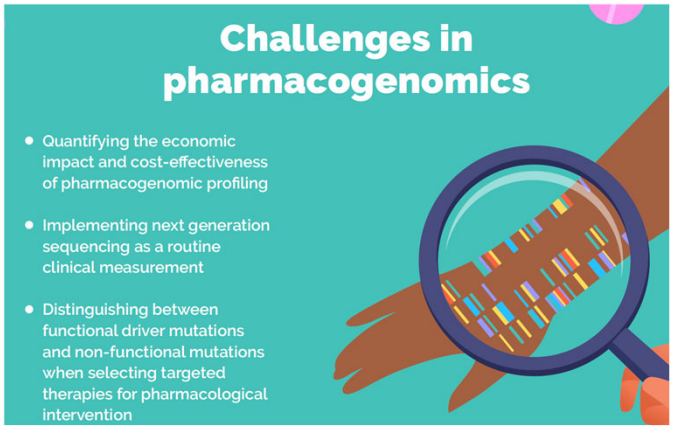
The implementation of large-scale genomic approaches to this question.
The study of the pattern of expression of genes involved in a drug response in a defined environment.

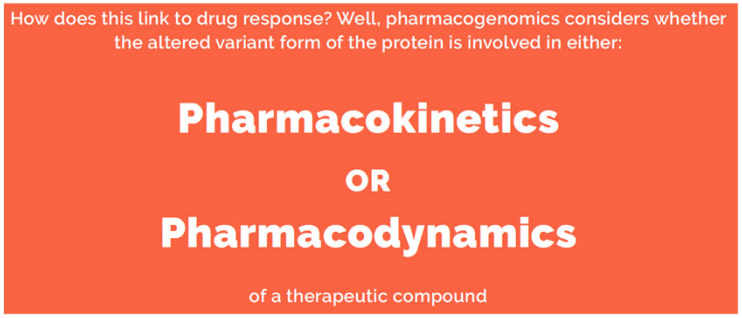
Pirmohamed 2001, Pharmacogenetics and pharmacogenomics

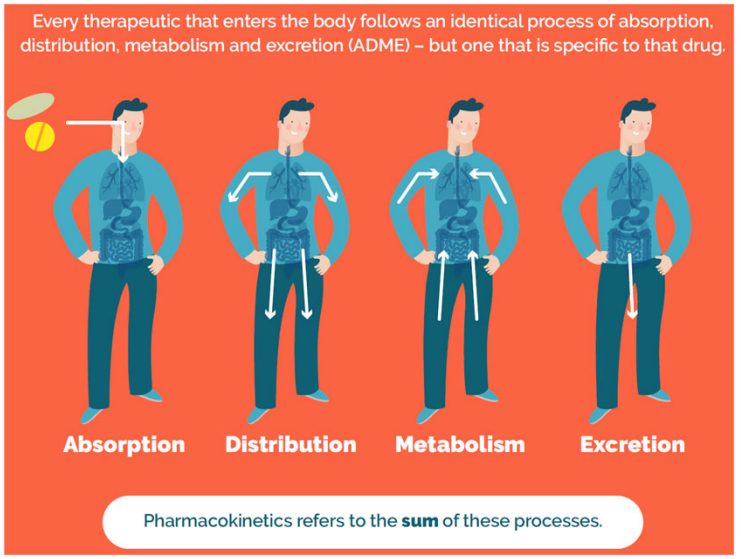


Precision Medicine

"Doctors have always recognized that every patient is unique, and doctors have always tried to tailor their treatments as best they can to individuals. You can match a blood transfusion to a blood type — that was an important discovery. What if matching a cancer cure to our genetic code was just as easy, just as standard? What if figuring out the right dose of medicine was as simple as taking our temperature?" (B.H. Obama 2015. The precision medicine initiative. https://obamawhitehouse.archives.gov/precision-medicine).

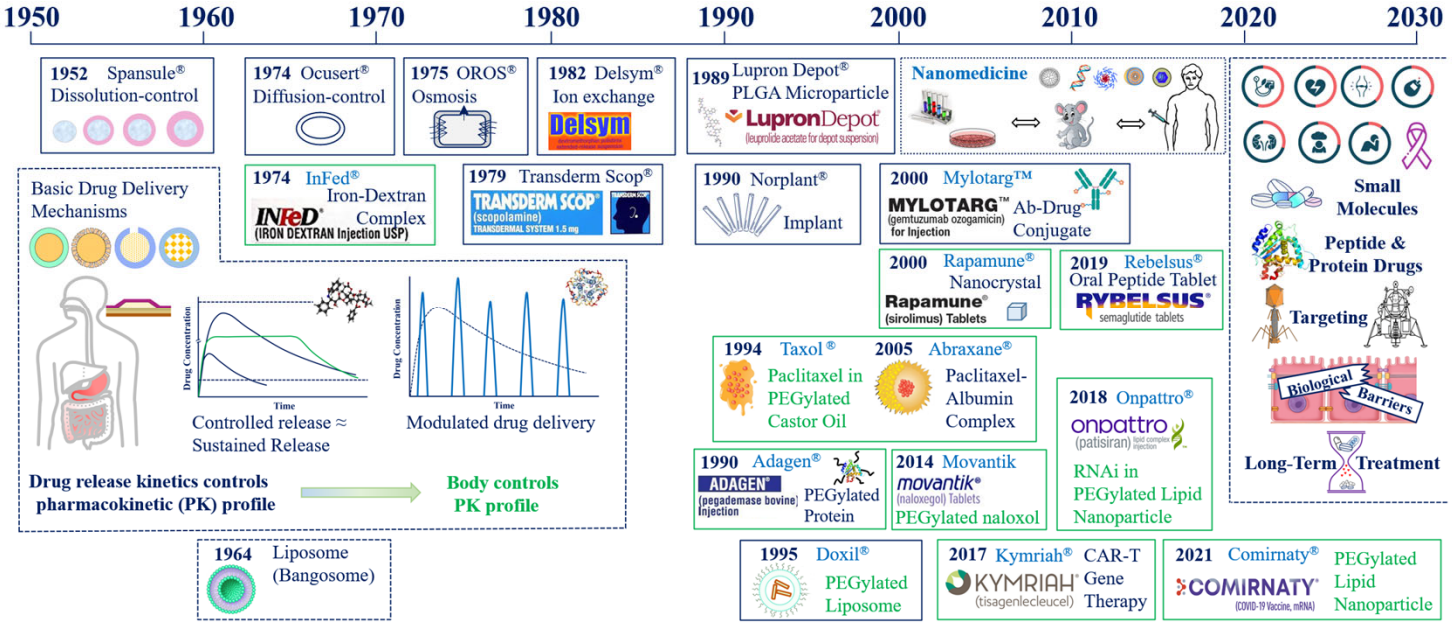






Technology Nwtworks 2020, Pharmacogenomics - Infographic

Challenges for Future Drug Delivery Systems



Oral / Transdermal delivery systems

Drug release kinetics by the system
In vitro release kinetics

⇩

In Vivo PK

Physicochemical properties
Engineering problems

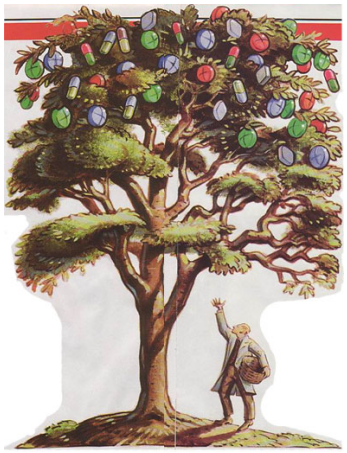
Injectable depot, Modulated, Nanomedicine

Drug release kinetics by the system
In vitro release kinetics

⇩

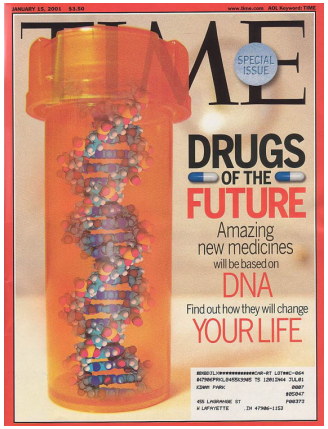
In Vivo PK

Physicochemical properties
Biological problems



Businessweek. May 6, 2002

Pfizer and Nektar's Exubera insulin inhaler (12 inches), 2006



TIME. January 15, 2001

Challenging Drug Delivery Technologies

Delivery Technology	Formulation Barriers	Biological Barriers
Poorly water-soluble drug delivery	• New excipients for increasing drug solubility	• Non-toxic to the body • No drug precipitation in the blood
Peptide/protein/ nucleic acid delivery	• Control of drug release kinetics • Control of drug loading • Control of therapeutic period	• IVIVC • Long-term delivery up to a year • Non-invasive delivery
Targeted drug delivery using nanoparticles	• Control of nanoparticle size, shape, surface chemistry, functionality, and flexibility. • Surface modification with ligands • Stimuli-sensitive delivery systems	• Controlling biodistribution through altering vascular extravasation, renal clearance, metabolism, etc. • Navigating microenvironment of diseased tissues to reach target cells • Crossing endothelial barriers (e.g., blood-brain barrier)
Self-regulated drug delivery	• Signal specificity & sensitivity • Fast responsive kinetics • Ability to stop drug release	• Functional inside the body • Functional over the lifetime of drug delivery