Meat by the molecule: making meat with plants and cells

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Our notion of meat has undergone a redefinition in recent years. New technologies for producing meat are challenging our assumptions regarding whether meat production need involve animal farming at all. In this article we'll explore opportunities in the growing fields of plant-based meat and clean meat, both of which are predicated upon the concept of deconstructing and reconstructing meat at the cellular and molecular level.

Rethinking meat: a critical challenge for our era

Global demand for meat is expected to increase by more than 70% between 2011 and 2050. This prediction is based on a combination of population growth and increased *per capita* demand especially in developing countries, where meat consumption has historically been relatively low. As this demand skyrockets, it is clear that the considerable resource burden, environmental harms, climate implications and public health risks posed by intensive industrialized animal agriculture are growing reasons for concern. At its most dire, there is a looming food security issue that cannot be ignored. There is simply not enough arable land – even if all the world's remaining forests were cleared – for us to continue producing meat in the way that we currently do. Incremental efficiency improvements are insufficient to get us past the fundamental thermodynamic Sisyphean challenge of funneling calories through a living, breathing, metabolizing animal. One could hardly dream up a more inefficient system for creating food.

Figure 1. Companies like Beyond Meat (plant-based chicken strips, left-hand side) and Impossible Foods (plant-based burger, right-hand side) have reimagined meat using plants. These newer products appeal to omnivores who are seeking to swap out meat at some meals — so-called "flexitarians" — which is driving the unprecedented growth of the plant-based meat category.

A pioneering collection of companies, academic researchers, and public and private funders are betting on the ability to make meat *without* the animal. There are two main approaches driving this paradigm shift. The first is developing plant-based meats: products that exhibit the taste, texture and full consumer experience of meat but are made from plant-sourced protein and other ingredients. (While "plant-based meat" is the common industry term, this approach also encompasses ingredients sourced from beyond the plant kingdom – such as fungi, algae, and even bacteria.) The other approach is to grow clean meat, which is genuine animal meat produced by cultivating animal cells rather than the whole animal.

Meat is undergoing a rebranding campaign. In the burgeoning realm of meat alternatives, meat is no longer defined by its origin or composition. It is defined by its structure, taste and role on our plate.

Food is biochemistry, and meat is no exception

Our deep cultural associations with food entice us to position it in the realm of the social sciences or perhaps even the arts. At its essence, however, food is humanity's romanticized version of Luria broth in a petri dish: it is the nutrient and energy source for our metabolizing bodies. But to a biochemist, there is something striking about the simplicity of this notion too. At the core, food is comprised of a set of biochemical molecules that, when combined and finessed in just the right way, can impart the complex sensory experience we associate with a particular food or meal.

Thus, the task of fundamentally rethinking meat entails viewing its creation as a matter of biological happenstance. Meat isn't an immutable, optimized food source. Rather, it is the confluence of events that resulted in animal muscle tissue of certain species appealing to our taste buds when prepared in certain ways. Understanding this allows for distilling meat's essence down to distinct molecular signatures (chemical and structural) that can be recapitulated with new source materials.

For example, can we use a combination of heat, a pH shift and shear stress to convert globular plant storage proteins into a fibrous, textured strand resembling the long chains of myosin and actin found in animal muscle? Can we canvass the plant kingdom for a protein that binds a haem group – and the iron bound within that haem group – to impart the metallic, meaty taste of red meat? Can we prospect for proteases and crosslinking enzymes that readily turn insoluble plant substrates into highly functional food ingredients?

Indeed, plant-based meat companies like Beyond Meat and Impossible Foods have already answered questions like these with a resounding yes and have brought the resulting game-changing products to market. As Dr Pat Brown, a renowned Stanford biochemistry Professor who left academia to found Impossible Foods, has noted, "the value proposition of meat has nothing to do with its coming from an animal."

Despite the considerable history of plant-based meat on the market, the realm of this industry is still in its infancy. There are a wide variety of plant sources – not to mention less obvious but perhaps even more sustainable raw materials like fungi and algae – that remain completely unexplored for their suitability in plant-based meat. Nearly all plant-based meat products currently on the market are predominantly comprised of soy protein, wheat protein and more recently pea protein, but the vast majority of other high-protein crops have not been utilized in these applications. Likewise, only a single strain of fungal protein has been commercialized as a meat alternative. And while a few algal food ingredient companies exist, these source materials largely have not made their way into the plant-based meat industry. For any given source of this biomass, the subsequent processing stages must be tailored and optimized, and these processes are entirely within the biochemist's domain. The first step is isolation or enrichment of the desired fraction (for example, to convert a pea flour that is 20% protein into a concentrate that is 80% protein). The second is functionalization, which includes chemical, biological and even mechanical methods for enhancing the ingredients' performance in a plant-based meat formulation from the perspective of taste, texture and nutrition.

The number of protein sources for which all of these methods have been optimized with plant-based meat in mind is abysmally small. The playing field is wide open for adapting these methods to new materials or for coming up with entirely novel and more innovative methods.

Cells, not animals, as the functional unit of meat

There is always a degree of mimicry involved when making meat from plant-sourced proteins and fats that are unavoidably different from their animal-derived counterparts. The fidelity of plant-based meats – their ability to recapitulate the full sensory experience of meat, from the aroma on the grill to the burst of encapsulated fat in each bite – has improved dramatically in recent years. Yet, this endeavour fundamentally relies upon identifying a set of critical components or structures that must be reproduced, rather making a molecularly indistinguishable version of meat. But there is another approach whose aim is precisely that: building genuine animal meat without the animal.

At its essence, meat is simply a collection of cells of various key types (muscle and fat are the most pertinent in mainstream cuts of meat) arranged in a matrix of connective tissue which contributes to the texture and structure of meat. Thanks to decades of animal cell culture research for basic biological and biomedical applications, there exists a wealth of information for growing all of these cell types and tissue structures *in vitro* – outside the body of an animal.

The basic process of clean meat production entails isolating a small number of cells from a donor animal. That starting population then expands exponentially through natural cell division, with the resulting cells seeded onto a 3D scaffolding material where the cells mature into the desired final cell types (muscle, fat and connective tissue). Biochemistry is critical to two main elements of the process: determining the nutrient composition of the cells' feed and designing the scaffolding material.

Within the nutrient feed, there are metabolizable energy sources (sugars, amino acids, fats), components that balance the salt and pH of the solution, and a small number of signalling molecules that trigger the cells to proliferate or transition into muscle or fat. All of these components must be optimized for each type of meat and cell line of interest. There is substantial potential to explore alternative components that perform better – for example, exhibiting higher stability in long-term culture or being more readily taken up by cells. The scaffolding material can be made of any edible, biocompatible material, such as a polysaccharide mesh that allows fluid and cells to migrate within it. Researchers have barely scratched the surface in terms of exploring biochemical modifications or linkages within the scaffold that could, for example, integrate flavouring components or cell signalling molecules.

The clean meat industry is still relatively nascent, but the number of researchers, startup companies and investors who are committing their time and resources to this endeavour has boomed in the last 2 years. There are now over a dozen startup companies pursuing clean meat, and industry partners ranging from meat companies to life science companies are starting to get involved. While the idea of growing meat from cells is not new, there seems to be a global consensus that we just now have enough tools to begin to pursue clean meat in an earnest way. This is truly a pivotal moment for our food system, from many angles, and the fundamental principles of biochemistry underlie this paradigm shift.

Biology is a talented architect and builder

The building blocks of biology are universal across all organisms: fatty acids, polysaccharides, amino acids and metabolites. The difference lies in the details: how they are arranged and the minute concentrations of subsets of molecules that serve as relatively unique fingerprints of a certain tissue type or class of organisms.

As a result, repositioning meat as simply one structural arrangement and formulation of these components allows us to reimagine the raw materials for making meat from a systems-level biochemical perspective.

We can envision giving value to biomass that was once considered a by-product from other industries by converting it into the perfect feedstock for these alternative meats. While animals evolved to tolerate only a limited set of biomass as inputs, cells can utilize sugars, amino acids and lipids derived from any source. Likewise, the plant-based meat industry has already found clever ways of utilizing the protein fraction of crops that have historically been grown for components like starch or oil (for example, the oilseed crop soy) by structuring it into enticing meat-like textures. And it's not just food and agriculture that have the potential to undergo a systemic efficiency reboot – there are opportunities to make use of side-streams from all sectors of the burgeoning bioeconomy including biofuels, biomaterials and industrial biotechnology. For example, companies like 3F Bio are utilizing nutrient-rich sidestreams from facilities like bioethanol refineries as a feedstock for high-quality protein, and some research groups are exploring modified plant cellulose – a byproduct from agriculture – as the basis for clean meat scaffolding. If the goal is ultimately a zero-waste system, one couldn't hope for a more versatile set of fundamental building blocks than those that have evolved in biological systems.

A call to action

In recent years, the notion of rethinking meat has gained considerable traction among groups who are in a position to support this approach financially and politically. For example, high-fidelity meat alternatives promise governments a path towards domestic food security while meeting the growing protein demands of their population. Investors and the food industry recognize the financial opportunity posed by a substantially more efficient production method. Finally, philanthropic groups for causes ranging from public health to environmental responsibility see the merits of supporting a transition away from intensive animal agriculture.

Increasingly, the bottleneck for accelerating the growth of the plant-based and clean meat industries is sourcing highly qualified technical talent. These companies are constantly seeking innovative scientists and engineers from a variety of backgrounds who possess a deep understanding of the fundamental biochemical nature of all cells, and therefore of all food. These are the creative minds driving technologies that challenge our notion of what meat is, how it can be produced, and how truly sustainable it can be – all while striving to satisfy consumers without sacrifice. ■

Further reading

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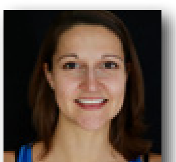

Liz Specht has a Bachelor's degree in Chemical Engineering from Johns Hopkins University and a doctorate in Biological Sciences from UC San Diego. Her research in academia focused on synthetic biology to leverage living systems for high-impact applications in biomedicine, energy and global health. She joined The Good Food Institute (GFI) once she realized that one of the most pressing challenges facing our planet today – building a more sustainable, healthier and more humane food system – is fundamentally a biotechnology-addressable issue too. At the GFI she works with startups, academics, industry, and both public and private funders to accelerate the development and commercialization of alternatives to industrialized animal agriculture. Email: lizs@gfi.org.