final report

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3D Printing of Meat – CryoLithography (RS3D) – stage 1 development

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Executive summary

This MLA project was funded with the goal of using 3D printing to transform low value meat into high value meat products. MLA has been investigating this platform technology as a potential enabler to transform meat inputs into higher value solutions for the Australian Red Meat industry (https://www.mla.com.au/news-and-events/industry-news/3d-printing-technology-for-value-added-red-meat/; and https://www.mla.com.au/research-and-development/search-rd-reports/final-report-details/Develop-New-Products/Review-of-market-acceptance-and-value-proposition-for-3D-printed-meat/3305).

3D printing, also known as additive manufacturing, is the act of rendering CAD models into physical objects through the layering of individual drops of additives one atop the other. For non-organic material such as plastic or metal, the primary attribute is the precision achieved in the creation of a final product. However the printing of organics (i.e. food) has many difficulties and issues needed to overcome including texture, layer cohesion and surviving the cooking process.

All food being printed must be turned into a slurry for it to flow through the extraction nozzle. Currently food that is 3D printed must also naturally harden at room temperature or have a thicker stickier nature to bind one layer to the proceeding layer: chocolate, dough, etc… Because foods such as meats must be converted into a slurry to flow through the extraction nozzle, the final output will have several issues such as a lack of texture or difficulty surviving the cooking process. In most cases the layers of meat 3D printed one on top of the other will separate if they are microwaved or baked.

Using a process created through research at the University of California at Berkeley in the lab of Professor Boris Rubinsky and with support and encouragement from the MLA, a new 3D printing process for meat was created that has texture, rigidity and can turn low value meat into high value meat products. MLA has commissioned this research project with RS3D to demonstrate its application to red meat.

The original work, known as CryoPrinting, focused on meat printed into a freezing liquid such as liquid nitrogen. As meat is extruded from the nozzle it solidifies in form, and with a stabilizer added to the slurry, will maintain that form once heated. This allows it to be baked and microwaved as well as fried without separating.

The instantaneous freezing of food slurry has several advantages over conventional freezing methods, namely control of ice crystal direction and size. As foods freeze, the natural occurring liquids in meats pool together and crystalize. The slower the freezing process the bigger the ice crystals. When the food is thawed, and the liquid melts, air pockets are formed in effect destroying the texture. Through CryoPrinting technology, all components of the food product are frozen at the same time reducing liquid pooling and therefore crystal size. As the entire printed object freezes at the same time, crystal growth also becomes uniform. An additional advantage of the freezing method is material preservation and reduction in spoilage.

The CryoPrinting process evolved from printing into a freeze inducing liquid, to a process known as 3D CryoLithography: A process of printing individual layers of meat into a desired shape and then stacking them to a specific height in a freeze inducing liquid. This process decreased the printing

time significantly but maintained all the advantages of CryoPrinting. This time savings is clear when looking at how current 3D printing is different than CryoLithography. Current 3D printing methods print over the same area multiple times to achieve the height and shape needed. Cryolithography lets you print one layer in multiple areas and stack them to achieve the height and shape needed.

CryoLithography has another advantage essential to turning low value meat into high value meat products: **Texture**. By printing an individual layer of meat, we are able to create similar texture to non-processed meat. Fibres are evident and meat can be pulled apart (raw or cooked) exposing those fibres. As subsequent layers are stacked they bind together creating seamless levels that do not break apart during cooking. The meat in this case also has the initial mouth feel of non-processed meat, but after a few bites breaks apart into a mashed potato like texture.

The fibres, initial mouth feel and subsequent texture change allows us to take low value meat and turn it into high value meat products in both the high protein snack food market and age care meals.

Potential Products for the Australia meat industry:

a) Snack Food Products:

Meat Floss: Meat floss is made by stewing bigger cuts of meat in a flavouring mixture then shredding, pounding and dry frying. The final product has a cotton candy like look and is dry, airy and salty in flavour. The meat floss process is expensive as it takes roughly 5 kilos of meat to turn into 1 kilo of meat floss. The requirement of stewing meat for multiple hours in order to break apart the collagen so that it can be shredded requires high energy resources and time. Further cooking and flavouring steps add to the time and resource requirements. Beef floss does however retail for roughly $150 USD per kilo on Amazon so the return on investment is significant. 3D printing of grained meat is a cheaper and faster alternative to the conventional meat floss preparation process. DMM meat with flavouring added, can be printed, fried and shredded. Not only is lower value meat being used in the initial process, but energy requirements and overall steps are significantly reduced.

High Protein Meat Snacks:

Meat must be transformed into a slurry in order to print and can therefore be combined with other ingredients such as fruits, vegetables and flavouring. Once the slurry is created, it can be printed in any form and baked or fried. This opens the door to multiple combinations, shapes and sizes of high protein meat snacks that can be packages and sold in multiple ways.

b) Meat for eldery populations and those suffering from dysphagia:

A 2012 Harvard University National Health Survey concluded that 1 in 25 people suffer from some form of chewing or swallowing issues. These issues are attributed to factors ranging from age to stroke to cancer. Those suffering from dysphagia currently eat some form of soft food or gruel which is both unappetizing and socially awkward. Taking into account only developed countries with means to purchase beef and lamb, this population numbers roughly 123 million people worldwide. At 2 – 3 meals a day over 365 days a year, the potential new market for meat that can be eaten at the dinner table or hospital by a growing population with no social stigma is enormous.

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1 Background

1.1 Project Undertaking

1.1.1 Project Background

Research for 3D printing of meat products has numerous benefits for the Australian beef and lamb industry which this project tried to explore.

As an example (using the American butchering method) A 1200 pound steer, ½ inch fat, average muscling, yields a 750 pound carcass. This carcass yields approximately 490 pounds of boneless trimmed beef, 150 pounds of fat trim and 110 pounds of bone. To break it down further, 185 pounds is low value lean trim or ground beef while the other 300 are turned into more valuable roasts and steaks. This means that roughly 40% of a steer turns into low value meat products like ground, filler or sausage.

40% is a sizable portion of return not to receive top dollar for a given investment.

Using 3D printing to turn even some of this 40% low value meat into high value meat products will not only bring a higher per head return, it will reduce waste from cattle and lamb and bring new products to market developing new revenue streams. The reduction in environmental impact as more meat is turned into useful product is an added bonus.

2 Project objectives

The project objectives were as followed:

Final Report – Describing:

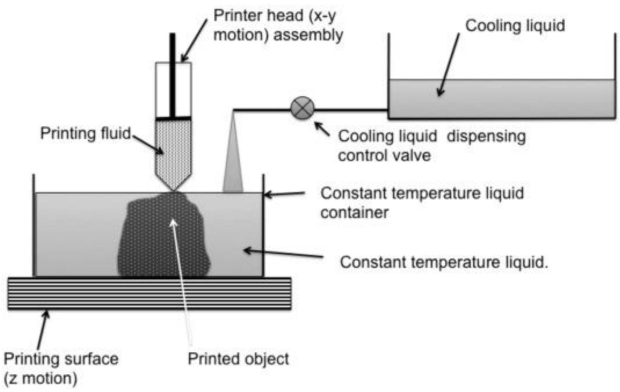
a. Technology platform & learnings applied to red meat based ready meals for dysphagia sufferers.
b. Bill of materials – Input and final product specifications, yields and costs (including modelling for wider adoption and impact on Australian red meat created/captured value for transforming commodity meat with RS3D into ready meals for aged care dysphagia market.
c. Feedback from workshops and next steps recommendations to scale up into industrial stage – technical feasibility and commercial viability including licensing of the technology to Australian red meat users and validation of the product-market fit value proposition (including willingness of the target consumer to change and pay for this offer and related food processing and labelling compliance to produce)
d. (Listed in appendix) Complete Business Model Canvass tool capturing key assumptions, learnings and insights in terms of desirability – feasibility – viability for this opportunity)

3 Methodology

3.1 3D printing of biological material

3.1.1 CryoPrinter

The original concept was to convert a standard 3D printer with X/Y axis movement to print directly into a freeze inducing liquid such as liquid nitrogen. Adding a stepper motor to the receiving plate, the receiving plate could be filled with liquid nitrogen and lowered as subsequent layers of liquid nitrogen was poured into the collection plate equivalent to the height of the next layer of printed material. In essence a new layer of printed material printed into a new layer of liquid nitrogen cause each additional layer of material to freeze to the previous one.



Printing into a freeze inducing liquid has many advantages for 3D printing biological material. Chief among those are:

- Cell viability as the cells are instantaneously preserved
- Reduction in cell damage as ice crystal growth is limited due to the speed of freeze induction
- Control of shape creation as layers do not shift once printed

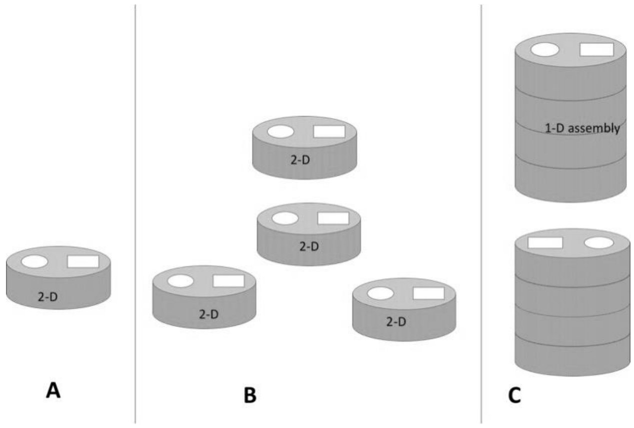
Additional advantages beyond those originally theorized included:

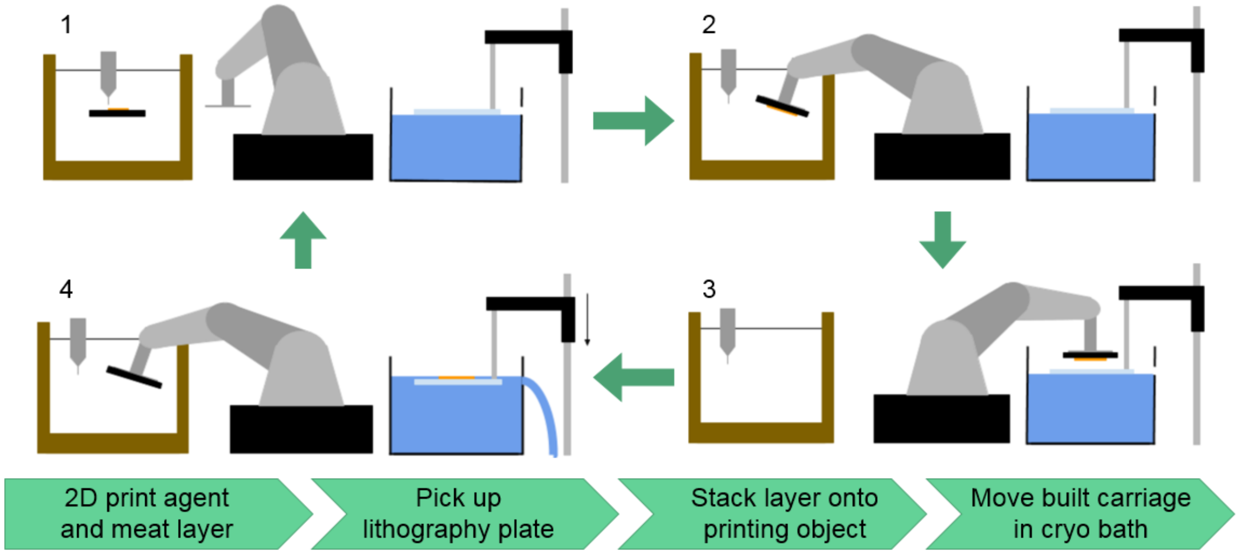
- Directional ice crystal growth causing increased adherence of one layer to the next
- Additional time and resource savings as items no longer go through the freezing process for shipment after their creation

3.1.2 CryoLithography

Through continued research and experimentation, this method of 3D printing directly into a freeze inducing liquid was replaced by a new concept referred to as 3D CryoLithography.

CryoLithography is the processes of 3D printing individual layers of a final product in separate locations and assembling them in a freeze inducing liquid using a robotic arm.





This method retains all the benefits of CryoPrinting but with two additional advantages:

- Graining of meat; creating fibres within each layer of printed meat
- Speed; 3D printing requires the printer to go over the same area several times to achieve the height desired. In traditional 3D printing the time to print five layers can be calculated as the time to print one layer multiplied by five. In CryoLithography since five layers are being printed in five locations and then combined, the time to print five layers is: the time it takes to print one layer plus the time it takes to combine five layers. If this is done on a conveyor belt, the assembly time is reduced to almost nothing.

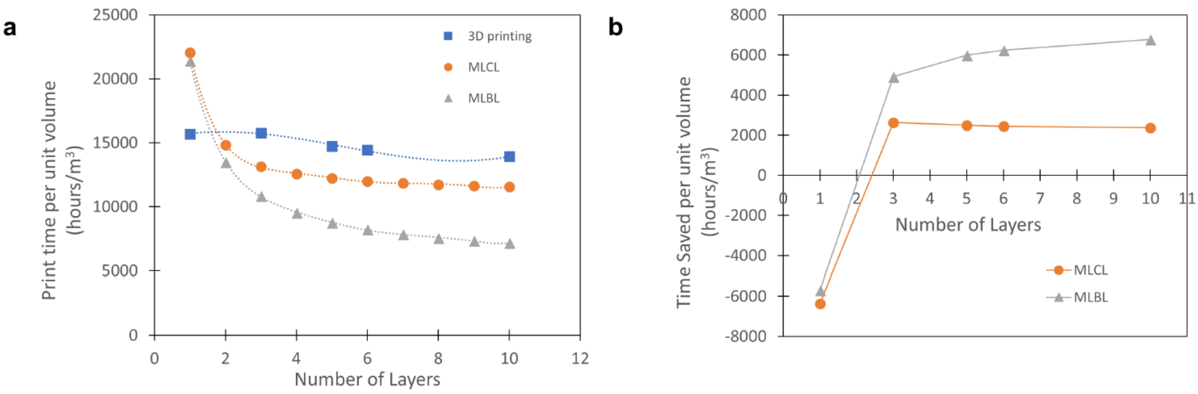
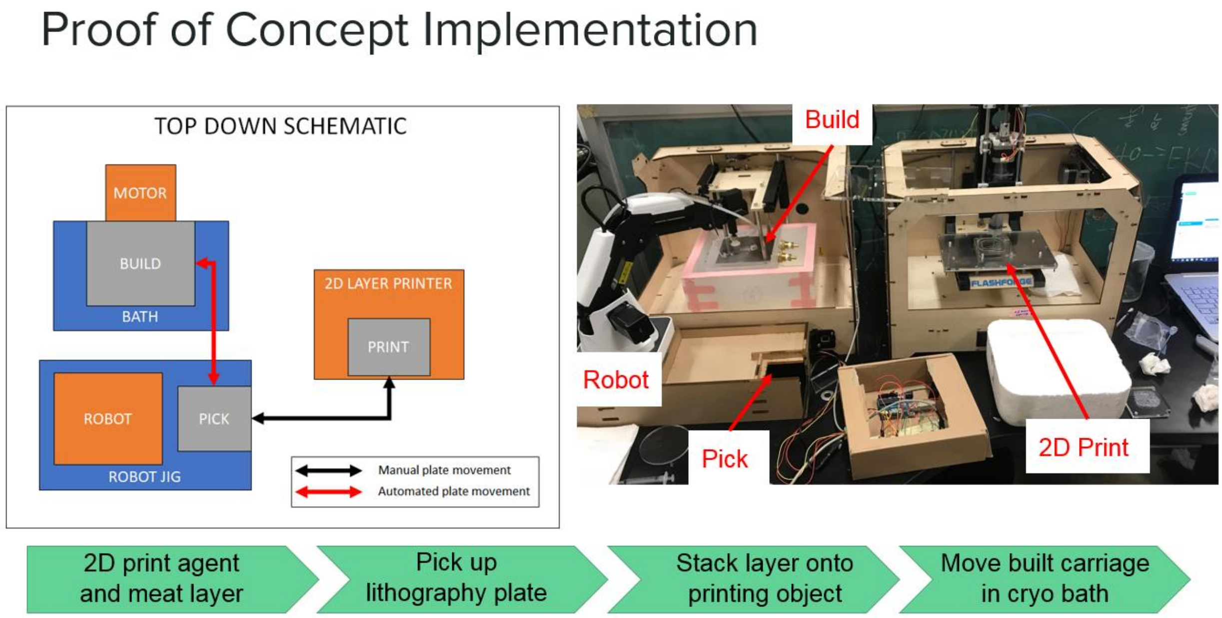
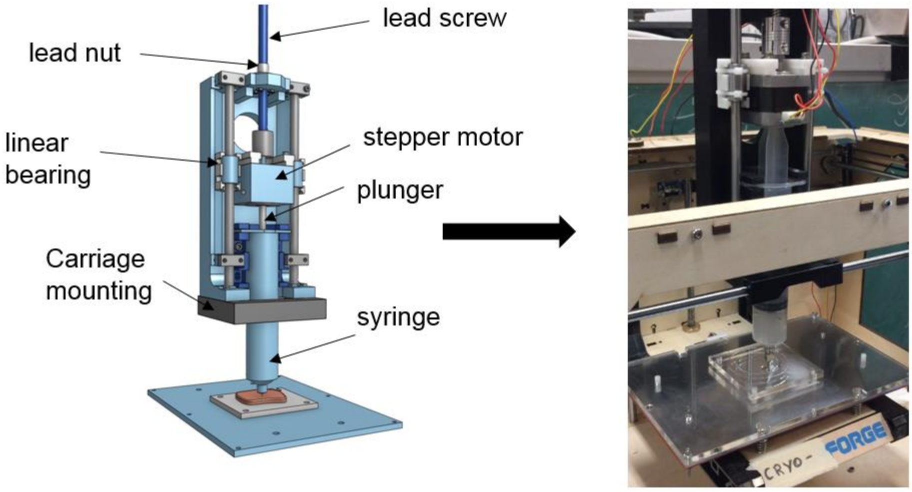


Figure comparing standard 3D printing to lithographic printing

3.1.3 Final Product Specifications

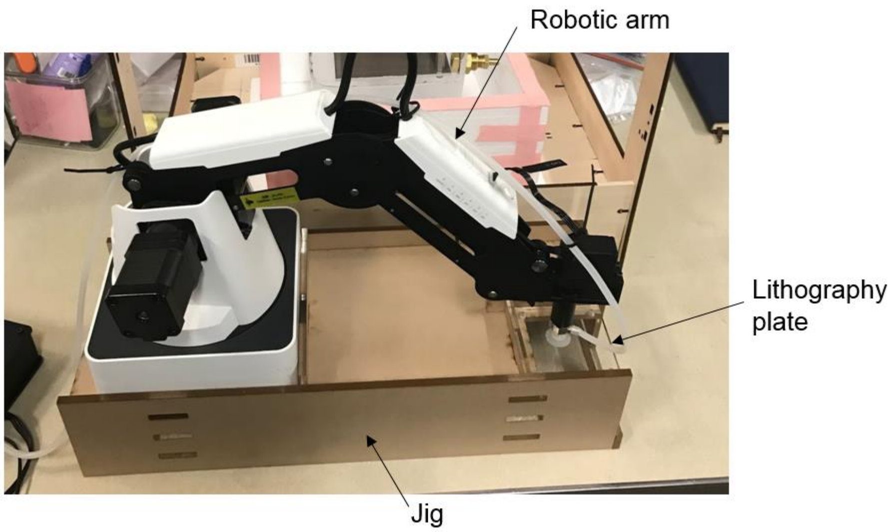


2D Layer Print Mechanism Design



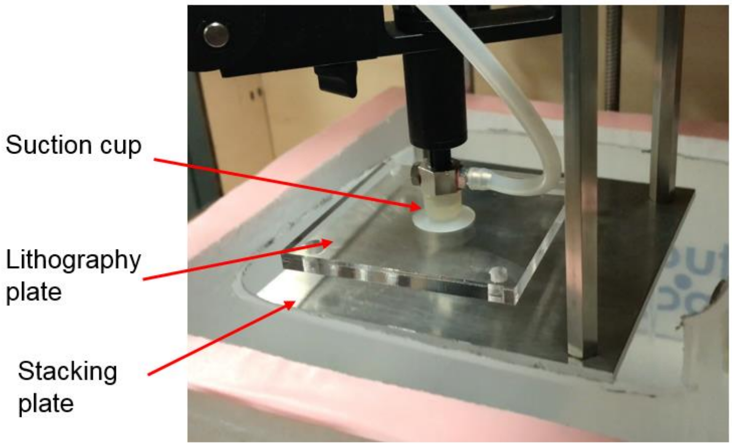
2D print agent and meat layer → Pick up lithography plate → Stack layer onto printing object → Move built carriage in cryo bath

Pickup Process



2D print agent and meat layer → **Pick up lithography plate** → Stack layer onto printing object → Move built carriage in cryo bath

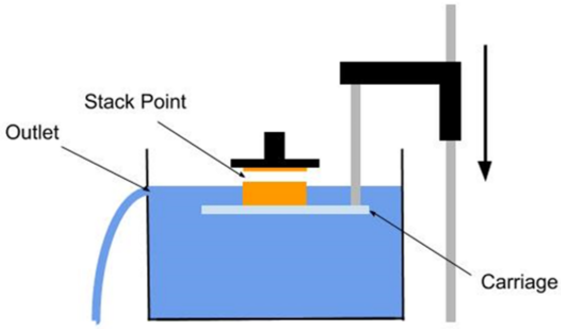
Stacking Process



2D print agent and meat layer → Pick up lithography plate → **Stack layer onto printing object** → Move built carriage in cryo bath

Move built carriage into cryogenic bath

- The stacking plate is dipped into the cryogenic bath
- The fluid level is held constant throughout the printing process



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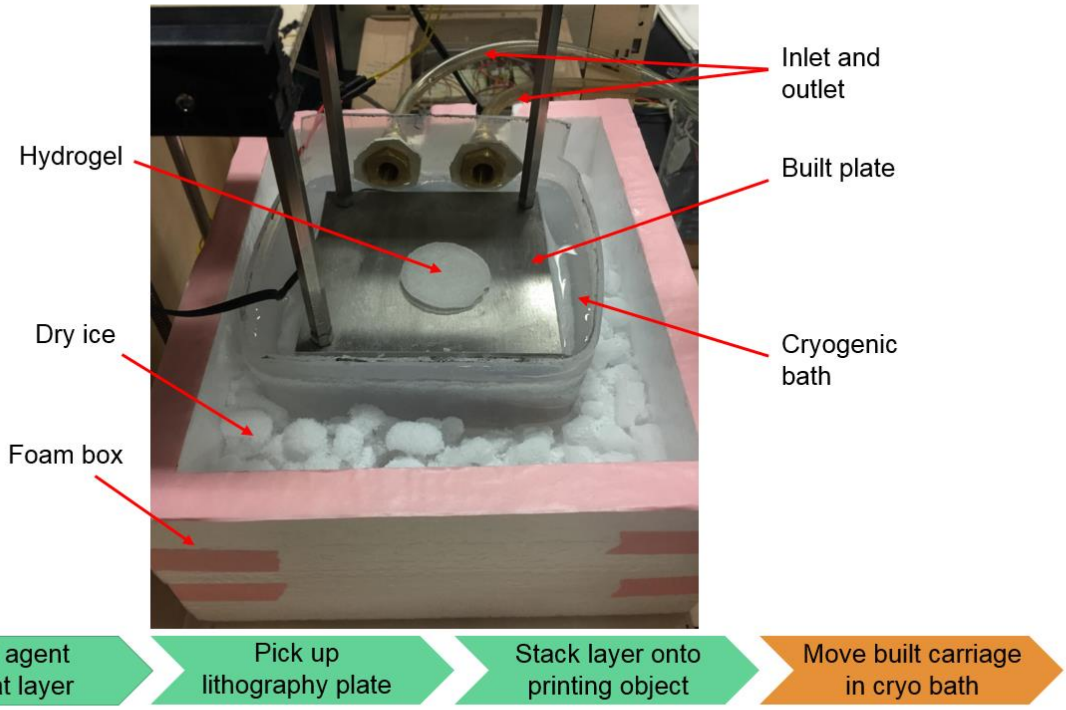


3.1.4 Input, Yields and Costs

The next phase of this project will turn the science proven in this phase into a mass production apparatus for the continual production of high value meat products from low value meat. This next step will allow us to extrapolate more accurate numbers to illustrate the complete economic advantage of this method. For this phase of the project and for the purposes of this report, we will use publicly shared numbers and projected results from the next phase of product development:

A 3D printer can extrude 50 to 150 mm of material per second. For non-precision printing as in the case of meat we can assume we would be at least in the middle level of 100 mm per second. This is the equivalent of 6,000 mm per minute. Based on an initial size estimate of our commercial 3D printer, we can fit nine heads in the area which could continuously print 3,240,000 mm per second or 3 K per hour. At 260 working days a year this leads to roughly 6,765 K of meat printed per machine per year.

Using ground beef with an original price tag of $2 US per kilo, the meat products produced can be turned and sold for $150 US per kilo in the case meat floss (not including processing and selling costs) or $5 - $10 US per kilo in the case of meat for patients with Dysphagia. The return on investment in this case at a low is 2.5 times inputs and 75 times inputs at a high. Using DMM or other lower value meat will only increase the return multiplier. Binding agents would represent a minimal cost.

The process of turning meat into a printable form is currently happening at meat manufacturing plants so production can increase and decrease with little planning and will have little cost effect for 3D printing. The amount of meat diverted from ground beef sold directly to consumers to new meat products will increase as market penetration and new product development increases.

4 Results

4.1 Overview of Market

4.1.1 Meat Floss

Through the project we believe we have found two possible markets for the Australian meat industry to target using 3D printing technology:

Beef and Lamb Floss (meat floss):

Printing of meat floss does not use the CryoLithographical aspects of the 3D printer, however the requirements of long meat fibres and rigidity does depend on a graining and binding method.

Meat floss is most commonly made from pork and is used predominantly throughout Asian and Africa as a garnish for meals, fillings for buns and as a snack.



While surrounded by high usage of pork floss throughout Asia and Africa, the 1.8 Billion Muslims living there do not consume it for religious reasons. With constant exposure to meat floss though, an alternative they can consume, like beef and lamb floss, would appear to be a welcome addition to their diet.

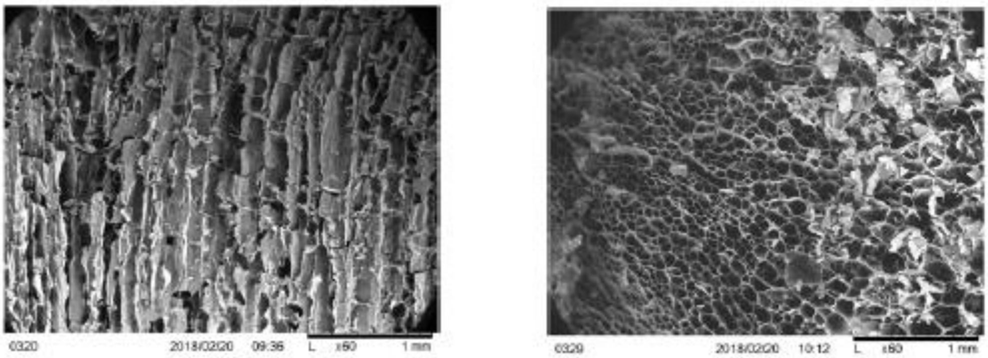
Meat floss is made by stewing cuts of meat like pork shoulder in a flavouring mixture that is then shredded, strained and dried in an oven. It's then mashed and beaten and dry fried with more flavour added.

The current process for producing meat floss is energy and resource heavy. Stewing the meat to break down the collagen to shred it takes multiple hours. Five kilos of high value meat turns into roughly one kilo of meat floss. The return on meat floss, especially beef and lamb floss is great though. While five kilos of meat cost roughly $50 at the store, one kilo of beef or lamb floss retails for about $150 on Amazon.

Because any item that is 3D printed needs to be turned into a slurry the meat used in creating 3D printed meat floss can be high value filet mignon or low value DMM with the results being the same. There is no stewing needed and flavouring can be mixed into the original slurry. Meat that can be turned into meat floss will come out flavoured with long fibres and texture, have a lower volume loss and require less time to create.

4.1.2 Meals for Aging and Dysphagia Populations

Through CryoLIthographic printing in an assembly line process, we can print multi layer meat products in any size or shape with an initial mouth feel similar to unprocessed meats but that breaks apart into a mashed potato texture after a few bites. Additional nutrients, fats, flavours and additives can be added to the slurry before printing.



Four layers of CryoLithographical printed meat

Two layers of uncooked 3D printed meat

A 2012 Harvard Medical school study found that 1 in 25 people suffer from some form of dysphagia or chewing problem. Dysphagia is a medical condition that includes difficulty starting to swallow and the sensation of food being stuck in the neck or chest. This issue arises for multiple reasons: Age, patients recovering from surgery, stroke, cancer or degenerative diseases. This condition affects similar percentages throughout every population in the world.

In more affluent areas of the world where beef and lamb are major parts of their diet (The United States, The EU, China, Japan, South Korea, South America, Eastern Europe and Australia) the total number of people suffering from this condition for at least 143 days per year are 123 Million.

Currently these 123 Million people eat pureed foods or mush which is both unappetizing and socially awkward. 3D CryoLithography printed meat that can be fried, baked or microwaved presents them with a solid meal alternative that satisfies all their nutritional and sensory needs.

5 Discussion

5.1 Results

5.1.1 Visiting Sydney

The overall objective of this project was to show that we could print multilayered meat products using low value meat that could then be turned into high value meat products.

This objective was completed as part of our printing demonstration at the MLA office in Sydney, Australia. The guests at this presentation included representatives from the MLA, industry, academia and the age care sector.

In Sydney, we were able to demonstrate successfully that we could print grained meat pieces and layer them using an electronic arm. We were also able to fry and share samples of the cooked meat. During our demonstration we received feedback from participants that the printed meat products had the initial mouth feel of non-processed meat and then broke up in a unique way. A representative from the age care sector commented that this could have multiple benefits for those he served including "adding fats and nutrition to their diets". Representatives from industry agreed that this was a "unique" product with potential.

What we demonstrated in Sydney presents an opportunity for the Australian beef and lamb industry to open new markets within the age industry and snack foods sector. Using the technology and adding varied cooking techniques and freeze drying allows the meat industry to turn their low value meats into high value meat products. The volume of meat moved from fillers into high value meat products will increase as market acceptance and product variations grow.

5.1.2 Additional Effects

A by-product of our research in 3D printing meat is that we believe this process can also have a very positive effect on livestock and the environment. Being able to extract more value per head will result in less food waste which will have a cascading effect on costs and land and water resources. Being conscious of the environmental impact, while also increasing the bottom line, brings true value not only to the Australian meat producer but to Australia as a whole.

The next step in our research is turning the science we have demonstrated into a mass production machine. This means continual printing of meat sheets that can be layered to create whole meat cuts for aging populations or shredding to produce meat floss. Additionally, as our research continues new products will come to light to increase the breadth of new high value meat snacks introduced to the market.

6 Conclusions/recommendations

6.1 Opportunities

The key take away from this project is that there is now an alternative for low value meat with multiple opportunities for new markets and new products. The science has been established and we have been able to create new meat products with non -processed meat mouth feel and textures.

We have high hopes for the future of our 3D meat printing project as we take our learnings and apply them into engineering a mass production apparatus for both whole cuts of meat and meat floss. A continued partnership with the MLA and livestock producers in Australia also gives us high hopes that Australian beef and lamb producers can take advantage of this new technology and open new product markets.

Moving forward we will work with the MLA to create an in depth market report and cost analysis for comparing our meat floss production process with standard meat floss production processes. This report will help us create partnerships within the Australian meat industry allowing us to produce 3D printed meat floss machines and license the technology in step one. Step two will be the creation of other 3D printed meat snacks with meat for patients suffering from dysphagia as a step three.

7 Appendix

7.1 Business Model

7.1.1 Key Partners:

- Meat Livestock Australia
  - This partnership helps RS3D understand requirements and goals of beef and lamb producers in Australia RS3D's target market.
- The University of California at Berkeley
  - All research is done through the university on an academic basis. Research is then licensed from the university to RS3D. As product development develops outside of academic research new labs must be established.
- Food manufacturing companies
  - RS3D is not a manufacturer of food but a research and licensing group. RS3D has no plans on manufacturing its own products but instead licensing its products and engineering knowledge.

7.1.2 Key Activates:

- New technology development
  - Develop new technologies that meet the needs of food manufacturing companies. From snack foods to processed steaks RS3D's key activities is to develop

technologies to reduce cost and transform low value meats into high value meat products.

- New product development
    - As new technologies are created, new product ideas arise. Sharing these new product ideas with key partners will allow RS3D to grow its portfolio of new products and new technologies for licensing deals.

7.1.3 Key Resources:

- Patents
    - While RS3D owns several patents for 3D printing and food manufacturing, as new technologies are created, patents must be established. Patents must be international and focus on technology, process and final goods.
- Patent lawyers
    - Turn around patents in an affordable and timely manner.
- Experimentation without requirements
    - Time to experiment and try new ideas without being beholden to timelines will allow for new products and processes to be developed.
- Engineering knowledge
    - Core to RS3D is experience in building new machines to build new products. This cannot be done without years of knowledge and experimentation methodology.
- Food manufacturing partnerships
    - RS3D is not a food manufacturer and does not want to become one. RS3D will only continue designing new technology and products in the food space as long as there are food manufacturers interested in partnering and representing RS3D.

7.1.4 Value Proposition:

- Product – market fit
    - 3D printing can provide foods with Personalised nutrition and customised texture
    - Ready meals and meat floss are two examples of a growing category (usage / occasion for high value read meat offer) and CryoLithography 3D Printed platform could be a unique way to make these types of products than traditional method.
- Engineering knowledge
    - RS3D has proprietary engineering knowledge and history. Years of experience will allow RS3D to work with its partners to develop new products for its customer base.
- Patents
    - From manufacturing to process, RS3D holds patents on the design and development of new and innovative processed meat products.

7.1.5 Customer Relationships:

- CO-Creation

  - Food manufacturing partners can suggest a product for development. RS3D can create the technology and process with a designated time-period of exclusive use or permeant ownership by the partner food manufacturer as a result.
- Development Partnership
  - RS3D can suggest new food products, technology and processes which food manufacturing partners can produce and distribute through exclusive or permanent ownership.
- Independent Development
  - RS3D can produce a new food product and partner with one or more food manufacturer to produce and distribute the product.

7.1.6 Customer Segments:

- Food manufacturing companies
  - RS3D will serve customers with already established customer bases looking for new and innovative products. These will be meat based products but can be developed in a way to increase nutrition, flavouring and texture.
    - Snack food manufacturing
    - Elderly food manufacturing
    - Hospital food manufacturing
    - Microwave meal manufacturing
    - Meat product manufacturers

7.1.7 Cost Structure:

- Engineering
  - Development of new technologies drive growth and product development.
- Legal fees
  - Domestic and international patents will be the bulk of legal fees but in return will also be the driver of revenue.

7.1.8 Revenue Stream:

- Licensing/usage fee
  - Partner manufacturing firms will pay RS3D a licensing fee for the initial technology and a usage fee on a volume or revenue basis.