High-pressure processing (HPP) decreases food spoilage and pathogenic flora and extends shelf life without losing sensory quality. Several national food health and safety agencies—including the French Anses—have issued approval statements concluding that cold-process high-pressure treatments are safe and effective on foods and food packaging. HPP can be applied in industry in several countries across Europe without special prior expertise, permitting or red tape. In 2010, the Anses formally recognized that a HPP treatment does not form harmful substances up to a process pressure of 600 MPa for 2 to 5 minutes. Food business operators do not have to compile, file and validate a process authorization application if they are working within these conditions. High-pressure processes inactivate certain microorganisms under specific pressure, temperature and hold-time conditions and according to food matrix. In meat products, the effect is shaped by the salt and fat contents and the calcium ions present. The high process pressures have little effect on meat taste and aroma but do accentuate the perception of salt and spices as the process alters the meat proteins and releases bound sodium. The unsaturated fat gets oxidized, which modifies both the taste and nutritional value of fattier products. Meat colour also gets modified as the myoglobin gets altered. This study found that HPP costs vary between €0.21 and €0.80 per kg of packaged retail-ready product.

The HPP process improves both the shelf life and technological yield of charcuterie products. It guarantees Listeria-free retail-ready products. There are still no predictive models available, so each and every HPP treatment must first be validated by on-matrix trials to determine its actual taste-texture and bactericidal effects. Although still expensive, the technology is readying for industrial scale-up on several product families and the EFSA’s scientific opinion is facilitating new application opportunities. Research is pressing ahead to support food business operators on process optimization and re-engineering for a wide range of products.

Keywords: high pressure, pathogenic flora, shelf life, colour, meat products, aroma, taste

Mots clés : haut pression, flore pathogène, DLC, couleur, produits carnés, odeur, saveur
Introduction

High-pressure treatment is making inroads in the charcuterie industry where it is increasingly being used to improve microbiological stability. This physical-mechanical treatment also has impacts—some positive, others negative—on the sensory attributes of the products processed. It is currently being run as a semi-continuous process that generates production-line input losses and stockpiles of intermediates, all of which drums up extra costs for the product-maker. This study set out to review the state of the art on technical, economic and regulatory factors to inform industry on the right conditions for employing HPP in the charcuterie business. HPP treatment is analyzed in terms of effects on product attributes, the costs entailed, and the economic feasibility of the process in order to determine the key conditions for applying HPP on charcuterie products.

Materials and Methods

High pressure processing (HPP), also known as high hydrostatic processing (HHP) or high-pressure pascalization (HPP), is a food preservation technology for microbial inactivation (cold pasteurization) developed commercially in the 1990s. Although originally geared to inactivating enzymes, its effects on the physical and taste–texture attributes of foods have served as a platform for wider integration into the processing of numerous different products. HPP offers an alternative to ionizing radiation or thermal treatments.

HPP—How it works

HPP technology is premised on increasing the pressure in a heavy-duty pressure-proof air-tight vessel, which compressively shrinks the volume of the products inside and thus has effects on the component molecules of the HPP-treated foods, i.e. conformation interactions, chemical reactions and phase changes. The pressure increase is delivered via a pressure transmission fluid—typically water. The process pressure delivered is isostatic as it is identical at all points in the vessel—and thus all points in the product. The target product has to be vacuum-packed in a packaging that is flexible enough to let it deform. Typical HPP system equipment found at the big food–farming industry processors today counts:

- a pressure-proof process vessel,
- a pressure intensifier pump,
- a high-pressure circuit governing fluid transfer between pump and process vessel,
- a system control and instrumentation cabinet.

On lab-scale equipment, the temperature of the pressure chamber, carrier basket and pressure-transmitting fluid is controlled by heating or cooling through a jacket surrounding the pressure vessel. On industrial-scale equipment, the temperature of the pressure chamber is not controlled but equilibrates with ambient temperature. The equipment is typically set up in a refrigerated coldroom.

The temperature of the pressure-transmitting fluid tank can be controlled by heating or cooling through a plate or serpentine heat exchanger. The high-pressure leak-before-burst seals used on the end-cap closures are the main driver of maintenance costs. There are subjected to repetitive wear cycles and have to withstand multiple series of a huge number HPP treatment cycles—each of which severely stresses the hardware. Like any other food-contact equipment, the whole assembly must be readily cleanable by design.

The indirect compression mode is the food–farming industry standard (at 200 to 800 MPa, or 2000 to 8000 atmospheres)

1. The baskets carrying the products to be HPPed are placed in the chamber which is then hermetically sealed and flooded full of water.
2. A high-pressure pump forces water into the chamber, thus producing an instantaneous and uniform (isostatic) increase in pressure.
3. Once the pressure has come up to setpoint, it is held for a pre-determined time somewhere between 2 and 7 minutes.
4. At the end of the treatment, the vessel is quickly depressurized before the chamber is opened and the product baskets recovered.

The pressure vessels can be either vertically or horizontally oriented. The mid-sized capacity systems can be set up vertically then tilted to facilitate product load-in and/or load-out. Available ceiling height, dimensions of the food processing plant, and the specific product to be processed may be factors for deciding pressure vessel configuration (Balasubramaniam 2016).

All process substep parameters need to be as tightly controlled as possible: packaging, preheat, temperature equilibration, pressurization, temperature increase through adiabatic compression (i.e. without heat transfer to or from the transmission medium), decompression, cooldown. The packaging needs to be designed to withstand the pasteurization treatment without losing integrity throughout subsequent time in food storage, i.e. to accommodate physical seal integrity, barrier properties, and risk of contact material-to-food migration. Process specifications for the target product are straightforward: no gas inclusions, pre-packed in a vacuum pouch, relatively flexible, with zero headspace.

Size and shape of the product are not influential factors:
- **Simple meat products**: fresh-butchered and processed meats, raw or cooked charcuteries—especially pre-sliced (currently the lead application).
- **Complex meat products**: pre-cooked and fresh-chilled ready-to-eat meals.

The HPP process is semi-continuous and features a treatment phase that stops product throughput mid-treatment cycle (chamber load-up, filling, pressure-up, treatment, depressurization, recovering the baskets). Throughput efficiency can be improved with two dephased machines running in a tandem system. The steady development of HPP high capacity facilities allows an industrial-throughput production. Computers are increasingly being used to control the pressure vessel operations and keep electronic records of the processes. The computer system will typically monitor process pressure, temperature, and hold time.

Process control remains limited by the shortage of in-system sensors and transducers. The pressures involved are so high that the vessels cannot readily be instrumented. Potential pressure transducer failure or drift are factors that need to be anticipated and addressed. Other considerations to include as part of the control system are the extent of plant automation for loading and unloading the carrier baskets, drying, and wrapping the packages ready for subsequent distribution. There is still no published pressure intensity/efficiency curve matching the pasteurization value used to gauge thermal process treatments.

**Economics**

**Food-industry uptake of HPP technology**

In 2007, there were 120 HPP machines equipping commercial food–and farming industries worldwide. When the PATS (pressure-assisted thermal sterilization) process was
FDA-approved for application on certain products in 2009, it sparked a surge in technology development that led to lower costs and wider openings for applications. At the end of 2011, over a quarter of the 162 industrial-scale HPP chambers around the world were in Europe (Lerasle 2012). In 2014, there were around 270 high-pressure machines in commercial service (a count that does not include pilot-plant or lab-scale machines) at around 200 companies around the world, representing a total vessel volume of about 55,000 litres. Estimates put global HPP food production at over 500 million kg. Most of the HPP equipment installed worldwide is used to process fruit and vegetable-based products (around 60% including fruit juices). At the end of 2015, the number of commercials-scale HPP machines in service passed the 350 units mark.

### The HPP foods market

In 2009, as world meat products output reached 250,412 metric tons, HPP meat products accounted for 90,215 tonnes (estimate given by C. Tonello, Hiperbaric), thus registering the biggest share (26%) of all purpose-treated foods.

**HPP products are a booming market** (Agro-Média, June 2015). It is a roughly $4 billion market that continues to register 20% growth per year, and projections point to $12 billion by 2018 according to Markets & Markets. Demand is strongest for ready-cooked foods, ‘health’-premium foods and animal feeds. HPP equipment sales are also climbing. Over 50% of global industrial-scale HPP equipment is installed in North America and Mexico (Wilches 2015). Europe is the second-biggest market for HPP, with the southern-Europe nations (Spain, Italy, France and Greece) leading the way and the UK catching up fast in western Europe. Uptake of this non-thermal technology is beginning to take off in emerging markets in Asia and South America. France counts the biggest HPP install portfolio yet does not host any HPP system manufacturers. The big new HPP toll processing business, which opens access to the technology without the heavy investment burden (as clients pay a per-cycle ‘toll’), is a big driver of HPP uptake across the food industry.

At the end of 2014, over 25 companies worldwide (toll processors or contract manufacturers) were offering HPP tolling services. Some HPP food processors provide HPP toll services while manufacturing their own HPP products, which enables effective and efficient utilization of their production capacity and thus faster amortization of their investment. **The meat products sector accounts for around 25% of the global HPP equipment install base (raw ground meat, dry sliced ham, cubed cooked or uncooked meat, ready-to-eat meals, poultry cuts and sausages).**

### Commercial equipment and vendors

The ‘big 12’ HPP system vendors worldwide count some that are either European or work specifically with European clients (Table 1).

Getting the right operations hinges on finding the right mix of machine parameters according to the pressure range, the heating and/or cooling systems, and the process vessel volume. **Different types of press** can be tailored to fit the following design characteristics (Table 2):

- **Configuration:** horizontal or vertical
- **Volume:** 55 litres (lab-scale trials) up to 550 litres (industrial-scale output).
- **Range of process pressure:** 600 MPa up to 1,400 MPa (lab-scale equipment)
- **Process temperature:** +20°C to +150°C.

**Horizontal design is the current standard** (94% of machines installed in the last 3 years were horizontal) as it carries clear advantages:

- **Improves product traceability** as products input and exit locations are at different sides of the equipment.
- **Physical segregation** avoids the risk of mixing or comingling between processed and non-processed products.
- **Increases production** as ergonomics eases the loading and unloading of products, speeds up the process, and avoids unnecessary use of cranes inside the plant.
- **Allows easier maintenance operations** in any part of the equipment and facilitates cleaning of the area.

**Fully automated load-in and load-out** is an increasingly popular option.

### Table 1: HPP equipment vendors in Europe (Balasubramaniam 2016). List is non-exhaustive

<table>
<thead>
<tr>
<th>Vendor</th>
<th>Address</th>
<th>Website</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avure Technologies</td>
<td>2601 South Verity Parkway, Middletown, OH 45044, USA</td>
<td><a href="http://www.avure.com">www.avure.com</a></td>
</tr>
<tr>
<td>Hiperbaric</td>
<td>Polígono Industrial Villalonquijar. C/Condado de Treviño, 6-09001 Burgos, Spain</td>
<td><a href="http://www.hiperbaric.com">www.hiperbaric.com</a></td>
</tr>
<tr>
<td>Multivac/uhde high pressure technologie</td>
<td>Multivac Sepp Haggenmueller GmbH &amp; Co. KG, Bahnhofstr. 4, D-87787 Wolferstschwenden, Germany</td>
<td><a href="http://www.multivac.com">www.multivac.com</a></td>
</tr>
<tr>
<td>Resato</td>
<td>Postbus 232, 8440 AE Heereneven, The Netherlands</td>
<td><a href="http://www.resato.com">www.resato.com</a></td>
</tr>
<tr>
<td>Unipress</td>
<td>Institute of High Pressure Physics, ul. Sokolowska 29/37, 01-142 Warsaw, Poland</td>
<td><a href="http://www.unipress.waw.pl">www.unipress.waw.pl</a></td>
</tr>
</tbody>
</table>
Technical and economic feasibility of high-pressure processing on charcuterie foods

Investment burden and operating costs

The main barrier to uptake of HPP technology is the big investment outlay needed to acquire and install the equipment and build the safety-coded environment (special protection walls) required for safe operation. HPP is therefore applied for high-added-value ‘premium-segment’ products that can be priced to absorb the added cost.

The capital cost of a high-pressure equipment system breaks down—very schematically—as shown in Table 3.

![Figure 4: AV-10 (throughput 1 ton/hour), at top AV-60 (throughput 2.6 tons/hour), at bottom](source)

![Figure 5: Hiperbaric 55 (throughput 266 kg/hour), at top Hiperbaric 525 (throughput 2.8 tons/hour), at bottom](source)

![Figure 6: HPP 55 – HPP 350 (throughput up to 4 tons/hour)](source)

Table 2: Cycle times and throughputs for various Hiperbaric machine systems (2015 online catalogue)

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Number of high-pressure pumps</th>
<th>Power (kW)</th>
<th>Cycle time* (minutes)</th>
<th>Cycles per hour</th>
<th>Vessel fill ratio</th>
<th>Output** kg/hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hiperbaric 55</td>
<td>1</td>
<td>55</td>
<td>6.2</td>
<td>9.7</td>
<td>50%</td>
<td>266</td>
</tr>
<tr>
<td>Hiperbaric 120</td>
<td>2</td>
<td>100</td>
<td>6.5</td>
<td>9.2</td>
<td>50%</td>
<td>555</td>
</tr>
<tr>
<td>Hiperbaric 135</td>
<td>4</td>
<td>190</td>
<td>5.6</td>
<td>10.8</td>
<td>55%</td>
<td>803</td>
</tr>
<tr>
<td>Hiperbaric 300</td>
<td>6</td>
<td>280</td>
<td>5.9</td>
<td>10.2</td>
<td>55%</td>
<td>1 168</td>
</tr>
<tr>
<td>Hiperbaric 420</td>
<td>8</td>
<td>370</td>
<td>6.7</td>
<td>9.0</td>
<td>60%</td>
<td>2 257</td>
</tr>
<tr>
<td>Hiperbaric 525</td>
<td>10</td>
<td>460</td>
<td>6.7</td>
<td>9.0</td>
<td>60%</td>
<td>2 821</td>
</tr>
</tbody>
</table>

(*) Total cycle time for vacuum-sealed prepacked products, including batch load-in and load-out, pressure come-up, 2-minute hold time at 600 MPa, decompression, and time needed for on-machine operations.

(**) Production output for vacuum-sealed prepacked products treated at 600 MPa (6,000 bars or 87,000 psi) for a 2-minute hold time.

Table 3: Capital cost breakdown of a typical high-pressure processing system (Balasubramaniam 2016)

<table>
<thead>
<tr>
<th>Cost component</th>
<th>Capital cost share</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-pressure vessel, closures, and yoke</td>
<td>50 – 60%</td>
</tr>
<tr>
<td>Pumping system</td>
<td>30 – 35%</td>
</tr>
<tr>
<td>Process control and allied instrumentation</td>
<td>10 – 15%</td>
</tr>
</tbody>
</table>

Net capital cost (75–80%) is a major cost for installing a commercial HPP plant.
Full operating cost (CEP 2015)

Total unit cost of the technology is calculated by factoring in two types of costs:

- **Amortization per unit (AU)** = initial outlay price divided by number of units produced by the machine through its useful life (average number of units produced each year × number of years of useful machine life).
- **Unit cost of operation (CUO)** = marginal HPP-related production costs divided by number of HPP-equipped units.

There is precious little published energy efficiency data. Hiperbaric (2015) claims an electricity consumption of 10 kWh/cycle (which equates to 700 kWh/day) for a 200-litre vessel running a pasteurization treatment (590 MPa, 2 min) under in-line production for 16h/day. Under the same conditions, in-line production for 200 days/year, with 20% of water volume lost at each cycle (60 litres/cycle), water consumption would be an estimated 1,700 m³/year.

This manufacturer data looks relatively optimistic (limited to investment cost). As commercial HPP technology is still in its infancy, there is little independent data available, so the IFIP ran its own cost simulations under different starting hypothesis scenarios. (Table 5).

The variables tested in a crosstab were:
- Net unit volume of processed product, in litres
- Process chamber capacity fill factor, in %
- Process chamber volume, in litres
- HPP cycle time, in minutes
- Batch-in and batch-out time, in minutes
- Number of operators required
- Tonnage output per day and per year
- Machine size—and consequently outlay price
- Amortization term.

Full cost varies from €0.21 to €0.80 per kg product pressure-processed depending on the hypothesis tested.

Analysis of the HPP technology

The French Ministry of Agriculture’s Centre for market intelligence and strategic foresight (CEP) has assessed the economics of HPP technology. The assessment was grounded as total cost per unit output (CUO), i.e. a final end-product on sale to consumers, such as a portion of food or a tray of meat. Compared to other food preservation processes, HPP emerged as a relatively expensive technology with fairly low machinery productivity. The high CUO of high-pressure processes ranks them among the most expensive technologies available, classed in a category dubbed very high total cost.

That said, HPP technologies do carry only modest operating costs when ratioed per kg product output. PATS (pressure-assisted thermal sterilization) is operationally far more cost-efficient that autoclave sterilization or tunnel sterilization. This HPP technology has relatively sub-par machine pro-

### Table 4: Example breakdown of production costs (with amortization)

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Throughput L/H</th>
<th>Productivity (600 MPa, 2-min hold time)</th>
<th>Price of the equipment, in €M</th>
<th>Cost of HPP treatment (½ amortization, ¼ spares and parts, ¼ labour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hiperbaric 55</td>
<td>55</td>
<td>266 kg/H 50% capacity-fill</td>
<td>0,5</td>
<td>20 centimes / kg</td>
</tr>
<tr>
<td>smallest-capacity machine</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hiperbaric 525</td>
<td>525</td>
<td>2,8 T/H 60% capacity-fill</td>
<td>2,5</td>
<td>7-8 centimes / kg</td>
</tr>
<tr>
<td>biggest-capacity machine</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: Hiperbaric

### Table 5: Results of full-cost modelling simulations

<table>
<thead>
<tr>
<th>Cost in € volume processed</th>
<th>Hypothesis with 100% OEE</th>
<th>Small-capacity machine, €500K</th>
<th>Big-capacity machine, €25,000K</th>
<th>Small-capacity machine</th>
<th>Big-capacity machine</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1 operator</td>
<td>2 operators</td>
<td>4 operators</td>
<td>2 operators</td>
</tr>
<tr>
<td>Direct</td>
<td>Labour</td>
<td>€0.16</td>
<td>€0.18</td>
<td>€0.04</td>
<td>€0.04</td>
</tr>
<tr>
<td></td>
<td>Product loss</td>
<td>€0.05</td>
<td>€0.01</td>
<td>€0.01</td>
<td>€0.01</td>
</tr>
<tr>
<td></td>
<td>Consumables*</td>
<td>€0.08</td>
<td>€0.08</td>
<td>€0.02</td>
<td>€0.02</td>
</tr>
<tr>
<td>Indirect</td>
<td>Machine investment schedule**</td>
<td>€0.45</td>
<td>€0.26</td>
<td>€0.28</td>
<td>€0.08</td>
</tr>
<tr>
<td></td>
<td>MR&amp;O***</td>
<td>€0.06</td>
<td>€0.06</td>
<td>€0.06</td>
<td>€0.06</td>
</tr>
<tr>
<td>Total, in €/kg</td>
<td></td>
<td>€0.80</td>
<td>€0.59</td>
<td>€0.41</td>
<td>€0.21</td>
</tr>
</tbody>
</table>

* water/utilities, oil, etc.; **7-year amortization term; *** 50% amortization cost

Source: IFIP (Nassy G.)
ductivity with a relatively modest throughput for the batch process (batch-by-batch output) and a capacity fill factor that proves tough to optimize. For the system to come out productively affordable, HPP treatment cycles will generally need to be no longer than 10 minutes—which looks viable given the figures released by system manufacturers or implemented in papers reporting technical studies.

The break-even of HPP technology can be described in terms of the production–possibility frontier between “possible/profitable products” and “low-added-value products that are not HPP-viable”. This tipping point is typically expressed in market value terms, i.e. price at point-of-sale.

Regulatory constraints

HPP is a novel production process, which means that both the process and its application to foods are governed by specific approvals and authorizations. In Europe, the governing frame of reference is the EU’s Novel Food regulation (EC regulation No. 258/97) for category f) that reads “foods and food ingredients to which has been applied a production process not currently used” [i.e. prior to 1997]. Any company that intends to apply HPP to food is required to apply to a competent authority (the consumer affairs and fraud control directorate ‘DGCCRF’ in France) for authorization. The application itself is a technical and scientific evidence report setting out the rationale and effectiveness of the process and—crucially—evidence that it presents no danger for consumers. A HPP food will only be approved for use if it is not nutritionally disadvantageous and not misleading to consumers.

In 2010, the Anses formally recognized that a HPP treatment does not form harmful substances up to a process pressure of 600 MPa for 2 to 5 minutes (ruling No. 2010-SA-0192 “concerning high hydrostatic pressure processing of prepackaged food”). Food business operators do not therefore have to compile, file and validate a European process authorization application if they are working within these conditions. The ruling has since been extended by ruling No. 2010-SA-0201 (Anses, 2010a) on impact assessments of (high-pressure-driven) pascalization on ready-made meals. In July 2011, Anses published an opinion “on the impact of high-pressure driven microbial stabilization processes on air-dried-and-smoked sliced duck magrets” (i.e. not air-dried-only magrets). In-scope food products had to have gone through every step in the conventional process, including processing into retail-ready packaging. Shelf life was capped at 90 days in unbroken cold-chain conditions. Process programme is: 5 minutes at 600 MPa pressure, core product temperature kept below 20°C throughout treatment, applied on food material that has been pre-sliced and vacuum-sealed in flexible packaging. The process hold time takes the product up to around 25°C before depressurization takes it back down to below 10°C.

The product, once further re-cooled down to +4°C, is then held in refrigerated cold-chain (max. +4°C) storage. Anses concluded that from a toxicology standpoint, the products were safe for consumers, and that HPP is efficient against vegetative bacterial pathogens and improves the microbiological safety of air-dried-and-smoked sliced duck magret. As HPP has no lethal baroprotective effect against spores, there is a risk that sporulating psychrotrophic bacterial will survive and thrive if Aw is increased under current industry state-of-the-art practice. Any change in formulation (such as lowering salt content) prompts the requirement for a new set of shelf-life studies.

A much-awaited shift in the regulations will come once the EFSA definitively lifts this constraint and recognizes HPP—if not wholesale, then at least for cold-process applications—as a routine-practice process outside Novel Food scope.

Consumer-side perception of HPP technology

One of the big advantages of treating foods with high pressure is that the food maintains fresh-like taste and quality characteristics. Physical-process preservation will always be preferred over chemical additives (CEP 2015). The ability to kill pathogens and spoilage organisms by a physical non-thermal process technology makes it a genuinely disruptive innovation, displacing other technologies, especially those that are more destructive (conventional thermal pasteurization) or less well accepted by consumers (ionization, chemical additives, etc.). Survey research has not found any negative factors disrupting final decision to purchase HPP foods. Rising consumer demand for better-tasting, additive-free, minimally-processed foods is a big driver of HPP technology uptake.

Each product’s amenability to HPP is a big factor shaping HPP consumer attitudes to the new HPP technology. F. Duranton (2012) found that consumer acceptance of a HPP product was heavily dependent on colour, lipid oxidation, protein oxidation, water retention, texture and aroma. At straight after treatment, HPP are just as acceptable if not better accepted by consumers than non-treated products: higher sensory quality scores were obtained with HPPed ostrich-meat sausage or ground pork meat.

However, consumer acceptability may tail off during storage when off-tastes or off-odours start to emerge. There is evidence that HPP treatment alters aromatic profile, as illustrated for example on dried beef products (500 MPa for 5 minutes) or cooked pork (600 MPa at 12°C for 5–10 minutes) that scored as less acceptable. There is a risk that consumers may shun HPP technology if it fails for retain product sensory quality durably throughout storage. These difference highlight the need to study the amenability of each product (meat type, preparation process, packing–packaging system) to the HPP regime applied (pressure, temperature, hold time).
The benefits: consumer-perceived advantages

Consumers interviewed consistently voiced a preference for fresh foods with a short shelf life. The longer shelf life enabled by HPP is not necessarily seen as an advantage in the eyes of consumers who believe that more shelf-life must equate to less freshness and thus ultimately a lower-quality food. HPP technologies do meet consumer expectations as:

- They are thought to be natural and less risk-ridden than some of the alternatives (ionization, sterilization).
- They can reduce or even dispense with the need for added food preservatives.
- They only apply to products that are pre-packaged but with no extra packaging added (environmental risks remain a consumer concern).
- High-pressure processing is thought to have little environmental impact, whereas conventional thermal treatments are more fossil-fuel-dependent, but the scholarship is inconclusive.

Price

Consumers are not willing to pay a premium for products that have a longer shelf life—which they see as a benefit for the food-business operators. Consumer perception is that longer shelf life is a natural technology-driven evolution, and so the switch in technology—and thus the cost of the new technology—is offset by the cost of the old one. Some consumers believe that prolonging a product’s shelf life reduces its intrinsic quality, and so the higher-shelf-life product should come at a lower price.

Consumer trust and regulatory governance

Most consumers were not against new food technologies per se but were unsure whether they will be exploited to hide fraud or whether their use will be strictly controlled and regulated precisely to prevent food fraud. They fear that certain processing technologies could use decontamination as a backdoor way to put out-of-date perishables back onto shelves.

Consumer scoring of HPP

Each participant surveyed was assigned a score ranging from minus two (most strongly against) to plus two (most strongly for). The positive opinions/negative opinions split highlights the very high number of consumers who are positively for high-pressure processes. These results are not generalizable as the sample was not statistically representative. Consumer attitude to HPP is fairly positive on aggregate: no extremely negative opinions, but nevertheless a non-negligible amount of negative opinion (-5) compared to positives or very positives (+10). HPP ranks as one of the “acceptable technologies” that meet the following criteria: less or no chemical preservatives, displacing high-tech processing by low-tech solutions that are simple, translatable, and perceived as ‘natural’. On balance, consumers are ready to accept high-pressure processes but without real conviction. The key selling point that talks to consumers is that HPP can replace chemical preservatives. Consumers harbour doubts over the potential negative effect of HPP on the nutritional and organoleptic properties of the food.

High-pressure machines are considered high-tech facilities that are probably out of realistically affordable reach. Demand is low as consumers have grown comfortable with the ‘good old’ pasteurization techniques.

Prospects for HPP expansion

A method has been developed to assess the attractiveness of food conservation technologies. Ten indexes—gauged on a scale of 1 to 10—are factored in to assess the attractiveness of the process:

- Feasibility of implementation: regulatory landscape, technology readiness level, maturity of the French market, acceptability,
- Macroeconomic impact: impact on waste efficiency, economic cost, environmental impact.

Feasibility of implementation

HPP is assessed as 5 out of 10 on the regulatory index. Even if HPP-treated products now escape the Novel Food regulations, there are still regulatory barriers as companies need EFSA-issued authorization to market an HPP-treated food. Looking to the 10-year horizon, the regulatory index can be expected to improve as the HPP technology will have matured and no longer be subject to EFSA authorization.

Technology readiness

HPP scores a 10 on technology readiness (already industry-proven) and maturity of the French market (already operational in France). The consumer acceptability rating for HPP (not a source of anxiety and eliminates chemical preservatives) is very good.

Macroeconomic and environmental impact

HPP are assessed as coming at very high economic impact due to the fact that the machines are burdened with huge investment input for relatively little productive output. Looking to the 10-year horizon, this index will improve if the technology cost gets significantly more affordable. Hardware standardization can help cut investment and production costs.

The attractiveness of HPP technology is expected to improve over the coming 10 years. In the CEP-led study, HPP ranked well and qualified among the group-1 food preservation technologies scoring over 5 (very promising) on attractiveness. Stacking up on top of effectiveness and acceptability, HPP is also more environmentally-frien-
High-pressure effects on meat products

The advantages of high-pressure processing technology on meat products are:

- **HPP is non-thermal**, refrigerated or ambient-temperature process.
- **HPP acts instantaneously and uniformly** independently of food and package shape/size (no pressure gradient, unlike thermal treatment).
- **HPP retains the fresh-like characteristics of the food** (little if any effect on in-food vitamins—including vitamin B12).
- **HPP efficiently kills most vegetative cells**: food pathogens and spoilage flora.
- **HPP increases shelf-life** which opens opportunities to reduce/eliminate the need for preservatives and additives (“clean label” statements).
- **HPP has low environmental impact**: far less energy-intensive than thermal food preservation systems, and all with relatively little water demand.

Pasteurization effect

High-pressure processes can inactivate in-food microorganisms under specific pressure, temperature and hold-time conditions that differ according to target-group microorganisms and food-matrix conditions. In meat products, the salt and fat contents and the calcium ions present are critical factors that dictate the results outcomes obtained.

There is still no published calculation model for assessing the effect of a high-pressure treatment to serve the same purpose as the pasteurization or sterilization values used to gauge thermal process treatments. Microbial inactivation by high-pressure processing is a complex process and microbial inactivation does not follow a first-order kinetics model. The inactivation curve often starts with a log-linear decrease that then tails. This tailing effect is due to nonhomogeneous treatment effect at microbial population scale and the existence of more pressure-resistant subpopulations of cells (Lerasle 2012). Recovery of bacterial activity is another major concern in meat products. High-pressure treatments from 400 MPa upwards significantly slow growth recovery and therefore, at equal hold-times, will decrease microbial load and increase shelf-life.

**Critical process parameters**

Process-driven **bacterial reduction increases with system pressure imposed** and it takes a pressure of 250 MPa to get a significant effect with hold-times short enough (1–5 minutes) to viably fit industrial purposes. A small fraction of microorganisms can survive the process-pressure stress. If they find the right environment, the injured cells can repair sublethal damage and recover growth.

In-storage recovery after high-pressure treatment is not a rare event.

The rate of pressure come-up and decompression is an equally critical treatment process parameter (Lerasle 2012). After a fast come-up time, an equally fast decompression time is reported to drive better inactivation of vegetative cells whereas a slower decompression is reported to trigger a ‘pressure-challenge’ stress response that makes treatment less effective. However, these results are challenged by other studies where slower rates of pressure come-up (1 MPa.s⁻¹) and decompression (5 MPa.s⁻¹) actually increased inactivation rates, as observed on *Bacillus subtilis*, whereas fast come-up followed by fast decompression time produced a greater population of sublethally injured cells. However, there is not conclusive evidence that multicyle treatment improves end-points. Alternating-pulse treatment does not necessarily achieve better outcomes than continuous treatment, even for longer net hold-times (several cycles for 15 minutes at 450 MPa vs uninterrupted 15 minutes at 450 MPa) in terms of destruction of psychrotrophic bacteria and mesophilic flora in poultry meat (at 20°C).

On *E. coli* O157:H7 at 12°C, a 400 MPa-per-cycle treatment with shorter bursts (two 15-minute cycles) has a greater lethal effect than a straight 20-minute cycle at 400 MPa. It appears that **straight-programme treatments** with pressure held steady are more effective that multi-cycle programmes, especially when using fast-rate pressure come-up and decompression.
Hold-time also influences the outcomes, but less so than pressure level imposed. One study showed that a 250 MPa treatment regime at 25°C led to a 5 log CFU/g reduction in *Escherichia coli* flora but that 6-log reduction was only reached after 1 hour exposure to the process. This tailing effect stems from the heterogeneous resistance to HPP treatment found in the bacterial population. In treatments under 30 minutes, the drop in microorganism count is sharp at the start of treatment then slows at the end of treatment (Lerasle 2012). This validates the decision to go with shorter-burst treatment cycles in industrial practice, which generally need to be no longer than 10 minutes.

Process temperature during exposure to treatment is visibly one of the most critical process factors for bacterial pressure resistance. For each type of microorganism, the pressure resistance curve peaks at a specific temperature (between 20 and 25°C) but shoulders off and drops faster as temperature strays further from this value. High-pressure treatment at moderate (i.e. less than cooking programme) temperatures often proves efficient. However, it has been demonstrated that a 50°C process temperature enables optimal efficiency against lactic acid bacteria, enterobacteria, mesophilic flora and *Pseudomonas*. The influence of exposure time is also dependent on the characteristics of the product treated. The food matrix protects microorganisms from the effects of imposed pressure. This baroprotective effect makes it necessary to work with a higher pressure level to achieve the same level of inactivation. Low water activity is reported to reduce HPP bacterial inactivation (Lerasle 2012). This baroprotective effect appears to kick in when aw drops below 0.92. For example, 690 MPa treatment with aw=0.92 failed to achieve bacterial inactivation of *Bacillus cereus*. Moreover, when aw was reduced to 0.83, *Listeria* inactivation decreased significantly. This net increase in barotolerance is believed to be due to the fact that at this aw, the cell proteins are stiff enough to not suffer denaturation by the high-pressure conditions. This same effect has been observed on *Escherichia coli* at aw=0.85. This effect appears stronger in the presence of nutrients and trace minerals (Ca²+, Mg²+). Furthermore, there is evidence that type of solute used to reduce in-media water activity has a greater influence on bacterial inactivation that water activity value per se. Thus, a high sodium chloride concentration was reported to protect *Lactococcus lactis*, *Escherichia coli* and *Listeria monocytogenes* during 500–600 MPa treatment (for 15 minutes at 20°C). The ideal food composition for effective destruction of microorganisms is products that are high in acids, high in aw (given the baroprotective effect of low aw) and low in lipids (as high fat content has a pressure-resistance effect, much like the temperature-resistance effect).

### Effect of microorganism type

Barring a handful of exceptions, the most high-pressure-sensitive organisms are:

- **Gram-negative vs Gram-positive bacteria** (although certain *Escherichia coli* strains remain very pressure-resistant). Pathogens like *Vibrio* and *Yersinia* (which are Gram-negative) are relatively high-pressure-sensitive and can be totally inactivated at 300 MPa, whereas *Staphylococcus aureus* (which is Gram-positive) requires pressures in excess of 500 MPa (Lerasle 2012). At 20°C, 6 log-unit reduction of *Pseudomonas fluorescens* (which is Gram-negative) was obtained at just 200 MPa whereas 400 MPa has to be applied to reach the same D-value reduction in *Listeria innocua* (which is Gram-positive).

- **Rod-shaped bacteria** (*bacilli*) are reportedly more high-pressure-sensitive that round-shaped bacteria (*cocci*).
• Yeasts and moulds are more high-pressure-sensitive than bacteria, and generally only require treatments delivered at between 200 and 400 MPa.

There is a huge array of cases that are difficult to predict, and differences are found between species, strains, and even serovars. The high-pressure effect may be overestimated, as there is evidence that the food-endogenous strains are more pressure-resistant that inoculation-challenge strains.

Relatively moderate process pressures decrease the growth rate and reproduction of vegetative bacteria whereas extremely high process pressures result in inactivation—the threshold is microorganism-dependent (Lerasle 2012). The bulk of research carried out over the past 20 years shows that process pressures ranging from 100 to 800 MPa and a given time–temperature combination will totally or partially inactivate vegetative bacteria.

HPP treatment against spoilage flora
As a rule, treatment at 200 MPa is enough to bring enterobacteria counts down to detectable levels, not just immediately post-treatment but also durably through shelf-life storage (Duranton 2012). At the end of in-storage shelf-life, germ levels are not necessarily lower than in non-treated controls. Certain flora are simply process-stressed and able to recover growth soon after treatment.

At 250 MPa and upwards, the anti-bacterial effect becomes significant. Sublethal process stress to bacteria translates as a biphasic curve with a longer lag phase before shouldering into a log phase that is recovered during in-storage shelf-life.

Treatment at 400 MPa and upwards will generally inactivate or at least significantly slow the growth of microorganisms and therefore increase meat product shelf-life. HPP inactivation is even stronger at 500 MPa, which is a high-enough pressure level to inactivate and efficiently slow bacterial growth. Bacterial behaviour responds differently according to type of spoilage flora, with process-resistance increasing along the following gradient: mesophilic aerobic bacteria, then lactic acid bacteria, then enterobacteria.

Salt contents up to 2% and moderate process pressures of 250 MPa have a synergistic effect producing a more efficient slowdown of endogenous bacterial growth. The thinking is that the high pressure induces metabolic injury to bacteria and prevents them from recovering growth in a challenging high-salt environment.

This synergism is also found between HPP and potassium lactate, a salt compound that decreases in-food aw and pH.

High-pressure treatment can radically destroy the lactic acid bacteria (Lactobacillus genus) that cause spoilage in vacuum-packed meat, with an 8.5-log CFU/g reduction found in a meat model treated at a pressure of 400 MPa at 17°C for 10 minutes.

However, subsequent recovery enabled growth to climb back to 6 log CFU/g after 20 days in storage at 4°C (Garriga 2002).

HPP treatment against pathogenic bacteria
HPP is used to sterilize certain foods due to its broad-action effects on Listeria monocytogenes, Escherichia coli, Salmonella, Vibrio and other groups, with or without adjunctive thermal inactivation treatment. Research is targeting synergies with other food preservation factors (antimicrobial action). The temperature bracket for peak bacterial pressure resistance is 10 to 20°C for Listeria monocytogenes and Staphylococcus aureus but actually spans from 20°C (excluding strain and pH effects) up to 27°C (with significant strain and pH effects).

HPP treatment is widely used on pre-sliced dry-cured ham to stabilize golden staph—to enable ambient-temperature distribution—and to eliminate Listeria monocytogenes—Listeria monocytogenes counts decrease proportionally with increasing process pressure: with a 10-minute hold-time, HPP at 100 MPa produces a 2-log-unit decrease in microbial load while HPP at 400 MPa yields a 7-log decrease (Lerasle 2012). This treatment enables guaranteed Listeria-free exportables.

HPP treatment against sporeformers
Bacterial spores are exceptionally resistant of high-pressure inactivation. HPP has to mobilize pressures of 1,200 to 1,500 MPa in order to achieve a 1.5 log-decimal reduction in bacterial spores, and a 14-hour treatment at 1,200 MPa failed to kill all Bacillus subtilis spores. Spore resistance is species- and strain-dependent, and Clostridium botulinum spores are the most treatment-resistant. It is necessary to apply a treatment regimen of 827 MPa for 30 minutes at 75°C to achieve any substantial reduction in Clostridium botulinum spores. Bacterial spores can also respond to a more subtle combination with low-pressure exposures (50–300 MPa). Spore inactivation by exposure to high-pressure treatment is visibly a two-step mechanism, where the first step at low or very-low pressure (50 to 300 MPa) induces spore germination and the second higher-pressure step (>400 MPa) inactivates the vegetative post-germination form. Bacillus subtilis in saline solution released 80% of its dipicolinic acid (the first sign of germination) after a 60 MPa treatment at 30°C (Lerasle 2012).

HPP cycling (at pressures from 690 up to 1,700 MPa at 60 to 90°C) have posted good results on relatively low-acid foods like meat products. Results recorded on Bacillus stearothermophilus spores under a continuous 600 MPa treatment at 70°C for 60 minutes were identical to those with a 400 MPa treatment at 70°C for 6 pulses of 5-minute cycles (Lerasle 2012).
Industry will need to combine high pressure and temperature treatment in a short hold-time window and longer exposure times and not economically viable. As the treatment is a batch rather than continuous process, the time factor has major impacts on productivity. Cold sterilization is not an option as bacterial spores resist a pure high-pressure treatment. Using water at a higher initial temperature in the pressure vessel makes it possible to reach an equivalent temperature to a sterilization technology called pressure-assisted thermal sterilization (PATS) (Barbosa-Canovas, 2014). PATS is a process route that uses modest preheat temperatures that start at 60°C–90°C, applied simultaneously with pressures of 600 MPa upwards, after which the in-food temperature rises to 90°C and then up to 120°C. This high-pressure, high-temperature, short-time process delivers strong-effect bacterial lethality.

The 6 steps in PATS process route (Barbosa-Canovas 2014):
1. vacuum packaging and load-up of the product
2. vessel water preheated to target temperature
3. product equilibration at initial ambient temperature
4. product temperature ramp-up to pressure come-up temperature during compression (adiabatic heating)
5. temperature decrease during decompression
6. chilling down to ambient temperature

PATS offers food processors the ability to produce superior-quality shelf-stable food products. Compared to ready-made meals thermally-stabilized in soft packaging, PATS gives better texture, denser colour, fresher flavour and better aroma retention. Not all meat products are PATS-viable as low production-scope capacity drives the cost up, which explains why PATS has made next to no inroads into the commercial market. Just like with conventional HPP, PATS-processed foods need to be high-added-value products that can be priced to absorb the added cost.

HPP treatment against viruses
Food science studies have shown that viruses are high-pressure-sensitive at low temperature. The hepatitis A virus (HAV) is not inactivatable at pressures under 400 MPa (Grove et al. 2008). It has been demonstrated that this inactivation is proportional to high-pressure hold-time. Treatment at 4000-bar pressure for 1 minute can yield a 3-log reduction in HAV (Grove et al. 2008, Calci et al. 2005) and 400 MPa for 5 min can reduce viral HAV titer load by a further 1 log unit.

HPP interactions with other technological factors
Interaction with sodium chloride
A 200 MPa treatment (10°C for 2 minutes) significantly improved the water retention of 1%-salt cooked minced beef, as juice losses were reduced by 75% compared to controls. This result is explained by the combination of salt-induced and pressure-induced protein denaturation. In meat foods including Strasbourg sausage that were HPPed at 600 MPa and 20°C, increasing NaCl contents (0.5%, 1.85% and 2.6%) decreased Listeria inactivation levels, thus confirming the baroprotective effect of NaCl highlighted in a number of studies and explained membrane protein stabilization due to either the high-pressure processing or the accumulation of osmoprotective compounds in the cell (conferring baroprotective on Lactococcus). Only the median salt content (1.85% NaCl) matches current food-industry practice.

These results now need to be cross-checked against partial substitution of sodium chloride with alternative chloride salts cleared for use under the French Code of Good Practice for Charcuterie, i.e. potassium, magnesium or calcium.

Interactions with antimicrobials
Nitrite is no longer an essential ingredient since food processors can now use HPP to produce microbiologically-acceptable nitrite-free charcuterie (Balasubramaniam, 2008). There is not yet evidence of any HPP/nitrite synergism in their microbiological action. The efficacy of antibacterial additives stacks up on top of the efficacy of HPP. A Salmonella enteridis inactivation study found evidence of significant synergism between HPP and some particularly efficient antibacterial additives — i.e. citric acid, sodium lactate and sodium acetate. A 600 MPa treatment was replaced by a 250 MPa treatment (at 25°C for 20 minutes) combined with antibacterial additives that delivered the same microbiological end-point. This same synergy has been verified on cooked ham with potassium lactate. Antibacterial peptides like nisin or enterocin LM-2 (which are not cleared for use under the French Code of Good Practice for Charcuterie) have a synergistic effect on Salmonella enteridis and Listeria monocytogenes when combined with high-pressure treatment at 400 MPa or 600 MPa for 10 minutes (Duranton 2012). Their antibacterial action is facilitated by the high-pressure action that causes permeabilization of the bacterial cell membranes, thus leaving them more exposed to the peptides. These synergisms do not align with the today’s market trend towards cutting down on food additives—even though the effects came from ‘natural’ additives.

HPP effects on meat and meat products
Water
The water that is native to fresh meat or added to help process meat products (brine in cooked ham, ice in soft-textured sausage batter) is a direct factor in the definition
of high-pressure processes. It plays a role in transmitting in-food pressure to the other in-food components. The compressibility of water is a function of pressure.

**Table 7: Decrease in the volume of water, at 20°C, as a function of pressure**

<table>
<thead>
<tr>
<th>Pressure (MPa)</th>
<th>100</th>
<th>200</th>
<th>600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decrease in volume, %</td>
<td>4</td>
<td>7</td>
<td>15</td>
</tr>
</tbody>
</table>

The work of compression will warm up the water by around 2°C per 100 MPa, depending on initial temperature. This same effect is exploited for PATS. Decompression causes an equally similar-magnitude cooldown. Combining pressure with heat makes it possible to work at a lower temperature and in a shorter window than with thermal sterilization while at the same increasing bacterial spore inactivation. **There is evidence that pre-germinating the spores makes them more inactivatable.**

HPP could thus be exploited to modulate freeze and thaw phase transitions. Pressure-freezing enables ice to nucleate rapidly and uniformly, forming smaller and therefore less product-destructive crystals.

Chilling products at 200 MPa down to -20°C (where the water is still in liquid state) then suddenly releasing the pressure leads to rapid and uniform formation of ice crystals, which is a key advantage over conventional freezing. The drawbacks of this process are the time needed to reach a perfectly uniform in-product temperature and a degree of deterioration in product appearance.

Pressure-thawing (at 210 to 280 MPa for beef) at very low temperature (-26°C to -22°C) shortens the process time independently of food size and start temperature, although it does induce some discolouration when process pressure climbs above 210 MPa.

## Proteins
### Protein structure
High-pressure processes have no effect on the primary structure of proteins (bond units connecting amino acids) but do influence their secondary structure and thus the general pattern of amino acid chain sequence in three-dimensional space. The hydrogen bonds either get broken or strengthened according to protein structure. Pressure in excess of 200 MPa can lead to irreversible protein folding in a denaturation process that is molecule, molecule-size and pressure regimen-dependent.

The secondary structural folding can cause certain proteins to aggregate. Process pressures in excess of 700 MPa cause irreversible changes in secondary structure. Process pressures in excess of 200 MPa can already alter tertiary protein structure, which modifies food protein functionality. Studies have observed the formation of multiple denatured forms, including transition state intermediates, as well as increases in the hydrophobicity of myofibrillar proteins tied to the pressure-induced exposure of hydrophobic regions. The mechanism of microorganism deactivation is explained by the denaturation of one or more protein components of the cell.

### Enzymes
In enzymes, the active site is carried by the protein’s tertiary structure and is therefore affected by the increase in pressure. This triggers a functional change—either a dissociation of the protein of a modification in the enzyme-catalyzed reaction. It takes pressures of over 100 to 200 MPa to inactivate the bulk of enzymes. Cathepsins and calpains—two enzymatic systems involved in the tenderization of meat during post-mortem aging—are essential to tenderization, and their activity is modified by high pressure processes.

High-pressure treatment of beef at 200 MPa decreases calpain activity by breaking down the mitochondrial membrane and sarcoplasmic reticulum and thus releasing calcium ions. Calpastatin, a specific calpain enzyme system inhibitor, is reportedly pressure-sensitive from 100 MPa upwards. Although key enzymes in the tenderization process can be activated by high pressure, their ultimate effect is tricky to discern.

The high-pressure effect on meat texture results from a combination of pressure effects—actions on proteins and actions on pre/post-rigor enzyme activity.

### Protein digestibility
High-pressure can irreversibly change food protein conformation. The resulting changes in protein-protein interactions, while substantial, have no effect on food macronutrient content and very little effect on nutritional quality. At pressures of up to 150 MPa, food proteins show no change—or any change that does occur remains reversible. From 200 MPa upwards, ambient-temperature pressure treatment can cause food proteins to denature, aggregate or, if pressure and protein concentration are high enough, to gel.

High-pressure treatments do not change food protein content but there is emerging evidence that they could increase protein digestibility. Pressure-denatured proteins are reported to be more sensitive to the actions of digestive enzymes.

### Carbohydrates
High-pressure processes have no effect on simple sugars but do affect polysaccharides and polysaccharide derivatives (starch, alginites, and others) and modify their gel- ing and thickening properties. Increasing process pressure up to 200 MPa decreased the melting temperature...
Technical and economic feasibility of high-pressure processing on charcuterie foods

of carrageenans (which are sometimes incorporated into standard hams as higher-yield binders). High-pressure treatment lowers the gelation temperature of starches (at different rates for different types of starch) and produces more shelf-stable gels. The fact that these starches retrograde more slowly that heat-gelatinized starches may make them more digestible.

Fats
High-pressure treatment from 200 MPa pressure upwards can increase lipid oxidation, especially meat lipids, which concomitantly increases free fatty acid content through the lipolysis of long-chain fatty acids. A number of relevant studies have been conducted, but the results do not converge. For example, the lipid peroxidation index of pork (whether minced or non-minced) shows little change at pressures below 200 MPa (at 20°C for 20 minutes) but increases with increasing pressure up to 800 MPa. HPP accelerates in-storage lipid peroxidation, but oxidation levels at the end of in-storage shelf-life remain identical to cooked controls.

In pork meat, pressure-induced acceleration of in-storage lipid peroxidation starts at 200 MPa. Treatments combining temperatures of 25 to 55°C with pressures of 400 to 600 MPa did not lead to increased TBARS (markers of oxidative stress) immediately post treatment nor through 20 days in-storage.

After high-pressure treatments of 200 and 400 MPa at 20°C for 15 minutes, dry-cured ham packed in 20% CO₂ modified-atmosphere packaging did not show accelerated lipid peroxidation whereas with 5% residual oxygen peroxidation emerged as a function of pressure applied, which underlines how residual oxygen plays a greater role than pressure. Accelerated lipid peroxidation in HPP products can best be avoided by opting for vacuum-pouch packaging and possibly also adding antioxidants. It has been reported that using citric acid at 0.2% abolishes the catalytic effect of high-pressure treatment on meat lipid oxidation.

The pressure-induced release of iron ions from myoglobin (or other heme-group metalloproteins) is reportedly one of the biggest accelerators of high pressure-induced lipid oxidation. However, this hypothesis is flawed, as lipid oxidation rate only starts to pick up at 200 MPa—a pressure level at which myoglobin remains unaffected. No change in non-heme-group iron has been observed in beef or poultry at pressures up to 500 MPa.

Another potential driver of accelerated lipid peroxidation could be cell membrane alterations, i.e. the rupture of adipocytes. Phospholipids are the cell membrane lipids that suffer the most oxidation from 250 MPa upwards (20°C for 20 minutes).

A 500 MPa treatment (at 20°C for 6 minutes) accelerates oxidation on minced raw and cooked pork samples (Guyon 2014). It acts in tandem with salt to speed up the formation of secondary metabolites of lipid peroxidation. These process events are slowed in the presence of at least 100 mg/kg sodium nitrite, which prevents the generation of long-term oxidants.

Combining the two food preservation techniques (applying high pressure and adding sodium nitrite) yields longer-shelf-life acceptable oxidation-level products, provided that oxygen is eliminated in the high-pressure-treated meat packaging (vacuum-packed) to avoid salt/process-driven lipid oxidation during storage.

HPP effects on product properties
High-pressure treatment improves product shelf life by reducing enzymatic activity and stabilizing certain key compounds (pigments, fats). However, it can cause unwanted alterations like discoloration.

Physical-chemical properties
Pressure come-up induces the water molecules to dissociate, which causes a reversible drop in pH of 0.2 to 0.5 units per 100 MPa increment. High-pressure treatment may therefore modulate certain pH-sensitive enzyme-catalyzed reactions, which warrants close microbiological surveillance.

Colouration
The colour changes induced by high-pressure treatment are a function process time, process temperature, and amount of fat. For pressures above 200 MPa, fresh pork is reported to go pale (increase in lightness, L*), and take on a grey-brown colour tone (decrease in a* redness index). For example, a decrease in a* in dry-cured ham was observed above 200 MPa, along with a concomitant decrease in b* yellowness index. The increase in L* is thought to

Figure 7: Colour variation in pork treated by ambient-temperature high-pressure processing (Duranton 2012)
be caused by the coagulation and denaturation of myoglobin (globin) proteins, which is reported to modify the absorbed light/reflected light split. The net result is that the opacity of the meat is affected. Partial denaturation of myoglobin and a decrease in myoglobin content are reported to affect a*, the redness index. At upwards of 500 MPa, the proportion of metmyoglobin (brownness) escalates whereas the proportion of oxymyoglobin (bright redness) drops. This oxidation of the myoglobin, which causes the unwanted brownish colour, occurs alongside an oxidation of other meat compounds.

The colour changes are less visible in cooked meat and even less in cured meat products. The colour stability of the pigment in cured meat (nitrosohemochrome) has been demonstrated (Duranton 2012) by equivalent colour measures between high-pressure-treated and untreated cooked meat products. However, the decrease in nitrite content in pressure-processed samples results in lower product appreciation scores. In a study investigating high pressure-treated fresh pork liver (Feurer 2015), a shift in colour and texture has been found that was related to the degradation of component proteins. This shift is visible from as early as 200 MPa and gradually continues up to 500 MPa. The appearance of coagulated protein exudates due to high-pressure treatment is observed from 280 MPa for 5 minutes, and results from a physical non-heat (adiabatic) process, a restructuring of protein structure, that leads to non-thermal coagulations and lends the livers a cooked appearance.

Corsican figatelli sausages were produced with these pig livers and HPP-tested frozen versus fresh: compared to non-treated pig liver figatelli, pressure treatment at 450 MPa for 2 minutes induced a slightly less red inner colour with both the frozen and fresh pig liver. High-pressure treatments at 400 MPa for 1 or 5 minutes produce little difference. Outer surface colour was discernibly redder and yellower (and thus browner overall) with the 450 MPa process compared to both the 1-minute and 5-minute 400 MPa treatments regardless of whether the initial pig liver material was fresh or frozen. The surface brownness showed up on all the HPP regimens tested (400 MPa for 2 minutes and 450 MPa for 1 minute and 5 minutes) compared to untreated controls.

**Texture / Tenderness**

Whole, minced or sliced products show different patterns of response. High-pressure treatment from 200 MPa upwards decreases the tenderness of post-rigor meat, as it drives muscle contraction and denaturation of myofibrillar proteins. This toughening effect is not as strong on slated meat.

**Taste**

High-pressure treatment often has no direct impact on meat product taste and flavour. It can act indirectly by limiting the development of the microorganisms that cause off-taste and off-odour during subsequent storage. Pressure-induced lipid oxidation can lead to rancidity and off-flavours. In meat products, high-pressure treatment can modify certain taste components by heightening the perception of spiciness and especially saltiness. This is attributed to the pressure-induced alterations to proteins that cause the release of protein-bound sodium ions. The most mobile sodium ions are more perceptible. This is an asset for low-sodium products, which offer a satisfactory saltiness taste but with a lower NaCl content. High-pressure treatments on dry-cured beef and dry-cured ham increase the perception of saltiness detected by a trained panel.

**Chemical safety of meat products**

There has been little research into the chemical safety of high-pressure-treated meat products. The few studies available show that high-pressure processes do not cause any major biochemical changes, with no cases of neoformed compounds reported to date. Nitrosamine and biogenic amine concentrations remain at least unchanged if not lower that in fresh meat product treated by more conventional processes.

**Biogenic amines**

In meat, the concentration of biogenic amines (tyramine, histamine, and others) is a function of bacterial population, free fatty acid concentration, pH, and process. High-pressure treatment to inactivate bacterial growth helped significantly decrease the in-storage concentrations of tyramine, putrescine and cadaverine in chorizo (250 MPa, 20°C, 15 min). However, spermidine concentration significantly increased biogenic amine levels in ham or meat batters treated at 200 MPa or higher.

**Nitrosamines**

High-pressure processing does not promote the formation of nitrosamines. HPP ham treated between 200 and 500 MPa, at 20°C, for 10 to 20 min showed no change in nitrosamine concentrations at 8 weeks in storage compared to non-HPP ham. Nitrite-brined meat batters reproduced this same no-change outcome. Using higher process temperatures thus served to reduce residual nitrite concentrations and, consequently, potential nitrosamination mechanisms.

**Allergens**

High pressure interferes with protein conformation, and conformational changes of proteins may alter antigenicity.
Studies have shown that HPP has no significant effect on allergen allergenicity, but meat products were not investigated.

Migration of packaging compounds
Migration testing studies show that high-pressure processing has no more (or even less) effect on packaging than conventional thermal treatment. Studies on stimulants used in migration testing for food contact materials showed that pressures up to 500 MPa (at 20°C) did not increase the migration of packaging compounds from PA-PE (polyamide-polyethylene) multilayer bags. Significant migration of compounds from the plastic material into beef and chicken breast was observed, but it was not enhanced by high-pressure treatment (400 MPa at 12°C for 1 minute). Net and specific migration rates are also lower—even at combined high-temperature high-pressure treatment—for food-grade polypropylene-based packaging.

Application on meat products

Fresh meat
High-pressure treatment (500 MPa at 20°C for 6 minutes) significantly increased juice losses and firmness in ground ham muscle cooked at 70°C (Duranton 2010). However, the presence of low salt content curbed these effects. Trials on whole muscle found that high-pressure treatment alone led to a tougher meat but that the presence of salt—even at the lowest concentration tested (15 g/kg)—abolished this effect. These findings have since been confirmed on polyphosphate-free meat products. High-pressure treatment has a whitening effect, caused by myoglobin denaturation, on both ground and unground meat, as well as significantly decreasing total vegetative flora, and this has been solidly confirmed, even after accelerating aging tests, with a synergism between high-pressure treatment and salt. On the basis of these findings, applying a HPP treatment should make it possible to create a very-low-salt product with acceptable technological yield and microbiological stability properties.

Cooked ham
A treatment well below levels found in industry practice (7 MPa for 4 seconds) replaced pulsed vacuum tumbling cycles for 6 hours (Bertram 2006). The resulting changes in sensory qualities were connected to in-product water properties: improved juiciness for low-salt (0.6% and 1.1% vs 1.7%) pressure-treated hams. At 0.6% salt content, pressure-treated hams appeared to taste saltier than the tumbled hams (non-significant difference). Peak intensity and total saltiness taste were significantly higher in the 0.6% and 1.1% salt-content pressure-treated hams.

These results show that the pressure process alters the structure and physical attributes of cooked ham, which suggests that high-pressure processing raises prospects for reducing the critical salt content in cooked ham, either instead of the tumbling process or, first off, in tandem with it. The latter hypothesis does not stand up against results reported by Tamm (2013), where post-tumbling HPP at 300 and 600 MPa led to significantly lower technological quality parameters at cooking and significantly higher firmness and colour variance than control hams. The products ultimately failed to pass acceptability criteria. Post-cooking HPP treatments led to significantly higher technological quality parameters that post-tumbling HPP treatments. The high-pressure treatment at 600 MPa, which yielded equivalent firmness to controls, appears to be the best pressure level for producing phosphate-added low-NaCl (12.2 g/kg) cooked ham.

Note too that ham colour remained unaffected, even at the highest process pressure. HPP appears to run into implementability issues during the cooked ham manufacturing process, given the mismatch between the batches sizes treatable and the amount of meat muscle industrial-scale processors need to work with. This is why HPP is generally applied on pre-sliced pre-packaged finished products to guarantee microbiological shelf-stability without compromising on sensory characteristics. However, HPP has improved shelf life. HPP at 600 MPa for 6 minutes at 31°C on cooked ham enabled a 4.6 log CFU/g reduction in lactic acid bacteria population (Jofre 2009), which remained significantly lower at the end of in-storage shelf-life than in non-treated samples. Furthermore, despite some recovery of lactic acid bacteria in cooked ham high pressure-treated at 400 MPa for 5 to 15 minutes, product shelf life was extended from 19 to 85 days (Slongo 2009).

Dry-cured ham

Microbiological effects
HPP at 600 MPa for 6 minutes at 31°C enabled a 1.6 log CFU/g reduction in lactic acid bacteria population (Jofre 2009). At the end of in-storage shelf-life, lactic acid bacteria levels were identical to control products characterizing a recovery effect (resumption of growth). However, dry-cured ham and fillet beef showed no recovery of endogenous lactic acid bacteria growth after 120 days in storage following a high-pressure treatment at 600 MPa. Cell recovery after high-pressure treatment thus remains a possibility, but one that is highly variable and heavily food...
matrix-dependent. A 600 MPa treatment for 6 minutes at 12°C has been used to produce smoked dry-cured ham with chloride and potassium lactate (Fulladosa 2009), and thus zero sodium, but the effect of pressure against Listeria and Salmonella was less efficient in these hams. On slices of smoked dry-cured ham spiked with Listeria monocytogenes and Salmonella at 100 CFU/g, high-pressure treatment at 600 MPa for 5 minutes eradicated pathogenic bacteria load in the NaCl-salted hams after 14 days (Stollewerk 2012) but the pressure effect was not as efficient in hams where the only salt used was potassium chloride and potassium lactate, as persistently detectable levels of Salmonella and L. monocytogenes were found at 28 and 56 days. Note, however, that in the non-pressure-treated hams, both germ types were consistently found right through to the end of the 112-day period of chilled storage, whereas they had declined faster in the NaCl-salted hams.

Effects on physical-chemical properties
High-pressure treatment significantly increased pH by 0.2 units in hams salted with 1.5% NaCl and by 0.3 units in hams salted with 1.5% NaCl + 2.4% potassium lactate (Fulladosa 2009). This increase was attributed to the conformation changes triggered by pressure-induced protein denaturation, leading to unfolding of the protein chains and the release of amino acids. This same effect has also been found on smoked dry-cured ham (Stollewerk 2012).

Immediately after treatment, pH was higher in the pressure-treated (600 MPa for 5 minutes) hams than all untreated hams, whether NaCl-salted (+0.09) or KCl and potassium lactate-salted (+0.18). After 112 days in storage, pH had not significantly changed any further, regardless of salt type and treatment group. No difference in aw was observed between pressure-treated and untreated hams (Stollewerk 2012) at day 1 in storage and again at day 112 in storage.

Effects on sensory attributes
High pressure significantly decreases water-binding capacity in dry-cured ham, which is reflected in the results of sensory analysis by taste panels that find significantly higher saltiness, umami and sweetness. The components responsible for these tastes (led by sodium) are more accessible to the taste buds and thus make perceived taste more intense. High pressure-treatment significantly increases the texture and brightness of dry-cured ham slices. It can also yield a degree of iridescence, which is a negative as consumers tend to associate it with bacterial growth or a sign of spoiled meat. Colour stability was significantly decreased. Immediately after high-pressure treatment, the pressure-treated hams were paler, redder and yellower (significantly higher L*, a* and b*) than the untreated hams. However, after 48 hours exposed to light, L* and b* continued to increase whereas a* decreased (all significant differences), to a point where redness index of the hams was no longer significantly higher than in untreated hams. The high-pressure treatment increased the firmness and cohesiveness of the dry-cured ham.

Myosins start to denature at a pressure of 100 MPa, and it is myosin aggregation that drives texture change in dry-cured ham. Other studies have shown that higher pressures (400 MPa) induce higher firmness, gumminess, fibrousness and cohesiveness in foods. This pressure effect could be exploited to reduce pastiness—a notorious consumer-averse texture problem in dry-cured ham.

Cooked sausage

Integrating HPP into food processing can improve the microbiological quality of the finished product by reducing contamination of the starting ingredients. The scale of effect is dependent on the intensity of the HPP treatment applied. For example, 150 MPa HPP was applied on fresh frankfurter sausage meat before comminution into bater (Crehan 2000) while NaCl was reduced from 2.5% to 1.5% without affecting consumer sensory acceptability. Indeed, the 1.5% NaCl formulation actually posted the highest acceptability score, which was explained by increased juiciness resulting from decreased juice loss. The 150 MPa pressure also had the effect of significantly decreasing cook loss and increasing the stability of the emulsion, whereas the 300 MPa pressure failed to achieve the same results.

The pressure-treated sausages were slightly—but not significantly—paler in colour than controls. The HPP-treated products were juicier with only slightly lower texture and overall acceptability scores than controls, and flavour and nutritional content were unaffected. This study provides solid arguments that a moderate HPP technology (150 MPa) is a viable process for improving the functionality of low-salt frankfurter formulations. Vacuum-packed cooked sausages were pressure-treated at 500 MPa for 5 to 15 minutes at a relatively moderate 65°C temperature (Mor-Mur 2003) and compared against sausages treated by cooking at conventional temperatures (80–85°C for 40 minutes). Colour remained unchanged. Pressure-treated sausages were more cohesive and less firm, and performed better on cooking loss. In some cases, there were no detectable differences—and when there was, panellists more often preferred the pressure-treated sausages for their better appearance, better taste and—overridingly—better texture. A set of different pressure levels (400, 600 or 800 MPa) applied cold at 5°C or warm at 40°C for 5 minutes were tested on vacuum-packed soft-textured pork sausages (Grossi 2012), where they induced an increase in water-binding capacity in the sausage mix core. With a 1.2% NaCl formulation and a 600 MPa and especially 800 MPa process pressure, water binding capacity approa-
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ched the same level as that achieved with a 1.8% NaCl formulation at 400 MPa. HPP at 800°C can thus be expected to viably decrease NaCl content from 1.8% down to 1.2%. At lower process pressure (400 MPa), the sausages had to be reformulated by combing 1.2% NaCl with 0.5% carrot fibre or 2% potatoe starch to reach equivalent cook-loss yields to a 1.8% NaCl formulation. Moderate-temperature heating (40°C) acted in synergy with high pressure by further improving the characteristics of these soft-textured sausages. Finally, HPP may have a role to play in helping bring to market not just low-salt foods but also the low-polyphosphate foods that processors and distributors are increasingly demanding. However, here again, integrating HPP into the food processing route poses implementability issues, especially as current industry HPP practice relies on ambient-temperature treatment.

Sausage and dry sausage

The pressure-induced decrease in pH conflates with the lower pH that occurs when fermenting sausage and dry sausage. Shifting pH away from the optimal value for bacterial survival enhances bacterial inactivation. Exposure to acidic pH also inhibits the recovery of sublethally pressure-injured cells (Lerasle 2012). Salted and air-cured chorizos and dry sausages featuring two different meat-mix materials were produced to achieve exactly 0.86 aw (Begona 2014). They were then inoculated with *Listeria monocytogenes*, vacuum-packed, HPP-treated at 600 MPa for 1 minute, then placed in chilled storage at 4°C for 120 days to track *Listeria* population kinetics. Pressure-induced log reduction in *Listeria* population was significantly lower on chorizo (1 log CFU/g without difference between meat-mix materials) than on dry sausage. Different pH was the explanatory factor. The bactericidal efficacy of HPP should therefore be determined on each HPP food matrix and with each bacterial target.

**Conclusion**

High-pressure processing has a sterilizing action that can significantly extend product shelf-life without losing organoleptic quality, including for certain foods for which thermal inactivation treatment is technically inviable, such as sliced and re-packed products. Another key asset of HPP is that it can be combined with other innovative food processing technologies to address challenges underpinning the “multiple barriers concept”—i.e. “softer” processing of foods to preserve naturalness while still efficiently ruling out pathogenic risk and extending shelf-life. To illustrate, HPP can be combined with biopreservation (the method consumers perceive as best) as it has moderate impact on the most resistant lactic acid bacteria, especially low-intensity HPP, which would let the ferment biopreservatives act in and on the finished product. Extended shelf-life before opening and better microbiological quality after opening are tangible advantages that consumers appreciate. Furthermore, the fact that HPP is applied cold and generally on foods pre-packed without headspace (vacuum-sealed pouches) opens prospects for using HPP in combination with shrink-wrapped active packaging materials engineered with active components that, although fragile, are completely inert to high pressure. HPP for food treatment is at a high technology readiness level, and the technology is even already industry-ready for certain applications. The scholarship needs to press ahead with research to support food business operators on process optimization and re-engineering for a wider range of products.

**Acknowledgements**

This study was funded by the French national programme for rural and agricultural development, INAPORC, FranceAgriMer, and the French Ministry for Agriculture and Food.

**References**

• Crehan (2000). Effects of salt level and high hydrostatic pressure processing on frankfurters formulated with 1.5 and 2.5% salt. Meat Science 55 (2000) 123-130.
• Garriga (2002). Bacterial synergism through bacteriocins and high pressure in a meat model system during storage. Food microbiology, 19, 509-518.
• Grossi (2012). Reduction of salt in pork sausages by the addition of carrot fibre or potato sarch and high-pressure treatment. Meat Science, 481-490.
• Hayes (2011). Monitoring the effects of high pressure processing, salt levels and refrigeration on the sensory and technological properties of pork sausages. 57th International Congress of Meat Science and Technology, Ghent-Belgium.
• Jofre (2009). Efficiency of high pressure at 600 MPa against food-borne microorganisms by challenge-tests on convenience meat products. Food Science and Technology, 42, 924-928.
• Tammeni (2013). Salt reduction in cooked ham by using high pressure processing. 59th International Congress of Meat Science and Technology, 18-23rd August 2013, Izmir, Turkey.

How to cite

Technical and economic feasibility of high-pressure processing on charcuterie foods