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Design of a new laboratory tumbling simulator for chunked meat: Analysis, reproduction and measurement of mechanical treatment

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ABSTRACT

Chunked meat is tumbled in large rotating drums, which is known to impact process yield and product quality. These impacts are mainly due to hundreds of falls, but no information is available on the actual mechanics involved. Both kinetics and rates of deformation were estimated from slow-motion films (1000 frames/s) of two types of ham muscles falling, duration and rate of muscle deformation varied from 20 to 120 ms and from a few % to 40%, respectively. A lab-scale device was built to reproduce these mechanical treatments and simulate what happens in industrial tumblers of various designs and sizes. Maximum force, deformation rate and dissipated energy of each deformation were calculated from force *versus* strain recordings. Dissipated energy was about 100 mJ or 500 mJ when deformation rate was 12 or 30%, respectively.

1. Introduction

Tumbling is a key step in the manufacture of cured and/or cooked meat products. Curing–tumbling is usually performed in baffled rotating drums, but processing conditions are highly variable due to differences in tumbler design and operating conditions (Martin, 2012). Industrial tumbler diameters range from 0.5 to 2 m whereas pilot-scale tumbler diameters are below 0.7 m. Furthermore, processing time and rotational speed are recipe-dependent, changing with pre-treatment, meat type, piece size, final product properties, and so on. Processing time is typically in the range 2–12 h, and rotational speed varies from 4 to 12 rpm. An intermittent regime is sometimes used that alternates rotating periods with rest periods. The mechanical energy which is transmitted to meat pieces due to falling and striking against the baffles leads to meat deformation.

Studies show that meat tumbling modifies meat tissue structure (Theno et al., 1978; Xargayo et al., 1998; Siro et al., 2009), enhances salt apparent diffusion (Dolata et al., 2004; Siro et al., 2009), promotes protein solubilization and extraction (Ghavimi et al., 1987; Kerry et al., 1999; Olkiewicz et al., 1995), improves cooking yield (Gillet et al., 1981; Dzudie and Okubanjo, 1999; Szerman et al., 2007) and gives better final product tenderness and juiciness (Ghavimi et al., 1987; Lachowicz et al., 2003; Hullberg and Lundstrom, 2004; Groenlund et al., 2007). All these studies into meat curing–tumbling were carried out in industrial or pilot tumblers of various types and sizes and with a lot of operating conditions. Unfortunately, the results are apparatus-dependent, and, except for the qualitative trends listed above, the quantitative impacts of tumbling cannot be related to the fundamental characteristics of the mechanical treatment undergone by meat chunks. Consequently, these studies cannot be used to tease out quantitative rules to optimize the tumbling protocol, and any attempt to transpose the conclusions from one study to another warrants heavy caution. Industry thus has to rely on a time-consuming trial-and-error approach to determine the best operating conditions for a given type of meat and a given recipe using a given tumbler.

It looks very difficult if not impossible to study the mechanical behaviour of meat pieces in industrial or pilot tumblers. Our aim here was therefore to develop a laboratory device that can simulate this mechanical treatment independently of tumbler design. We carried out a first set of experiments using slow-motion films to analyze meat deformation due to falls.

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List of symbols

Cr	compression or strain rate (–)
E	Young's or elastic modulus (Pa)
F	muscle reaction force (N)
Fmax	maximum muscle reaction force during compression (N)
Lc	length of muscle compression (m)
Mt	muscle mean thickness (m)
ν	Poisson ratio
RF	*Rectus femoris* pork muscle
SM	*Semimembranosus* pork muscle
S	piston-meat contact surface area (m^2)
t_D	duration of deformation (s)
σ	stress (F/S, Pa)
Ud	dissipated energy in meat during a deformation cycle (J)
Uk	kinetic energy (J)
Us	stored energy in meat at maximum deformation (J)

2. Basis of a tumbler simulator design brief

Meat processing inside a tumbler drum is illustrated in Fig. 1A. A layer of meat chunks is placed in the drum with either marinade or brine; the brine can also be injected into the meat during a previous step. Due to drum rotation, most of the meat pieces are taken by the baffles from the bottom to the top and fall down on the meat layer at a frequency that depends on rotation speed and number of baffles. Mean fall height is proportional to drum diameter but varies strongly between rotations since a piece of meat can fall before it reaches the top or even just remain in the bottom layer. Mean fall height is also dependent on tumbler fill, which in practice typically varies from 50% to 100% of nominal capacity. At the same time, drum rotation promotes mixing and consequently friction between a meat piece surface and either the drum wall or the surfaces of other meat pieces.

The mechanical action undergone by one meat piece is therefore very complex to plot and highly variable with time along tumbling. For the sake of simplicity, this mechanical action can be broken down into two main actions which should be reproduced separately for rational analysis:

- Action A – short deformation due to fall

  The kinetic energy accumulated during a fall, equal to the initial potential energy at the start of the fall, promotes a brief deformation of the meat piece on contact with the bottom layer. Since meat tissue does not have a pure elastic behaviour but a nonlinear viscoelastic behaviour (Lepetit, 1991; Lepetit and Culioli, 1994), the energy is partly dissipated during deformation and finally into heat. This mechanical action can be assimilated to a very short mechanical compression test. Initial potential energy is proportional to meat-piece weight and fall height, and it varies markedly; to illustrate, initial potential energy is equal to 0.25 J for a 100 g chunk falling from 25 cm but 15 J for a 1.5 kg chunk falling from 1 m.
- Action B – compression and friction during the periods between falls

  Within the bottom meat layer, a given meat piece undergoes compression and friction. The pressure exerted on one piece is proportional to the thickness of products above it, and compression duration depends on drum rotation speed. Contrary to action A, the resulting deformation is probably negligible because (i) the same pressure is applied over the whole piece surface and (ii) the bulk modulus of elasticity is close to that of water ($2\ 10^9$ Pa). Friction here is rather difficult to define: friction between meat pieces depends on their relative rotational speeds, but friction also occurs against the walls of the drum and the baffles. Both types of friction are probably influenced by contact pressure, and therefore by the position of the meat piece within the product layer.

Based on the studies cited in introduction, we can hypothesize that most of the alterations measured on the products were mainly dependent on the number of rotations imposed during a given experiment using a given device. In this scenario, action A has the biggest effect. It is therefore worth summarizing some of the key elements of 'impact loading' (Antonyuk et al., 2010; Wright, 2012) and 'viscoelasticity' (Bergström and Boyce, 1998; Ozkaya et al., 2012):

- When a body of mass m falls of a height H on a stiff plane surface its velocity v just before impact is determined by H and its kinetic energy Uk is equal to m $v^2/2$ and to mgH if drag force is neglected. The contact reaction force F act to slow the mass; deceleration is nearly infinite at the point of impact and the surface of contact increase with time. The result is a compression of the body in the direction of motion until F reaches its maximum Fmax (Wright, 2012). In the simplest case of an actual elastic sphere of mass m and radius R, assuming no energy dissipation, approximate functions of F

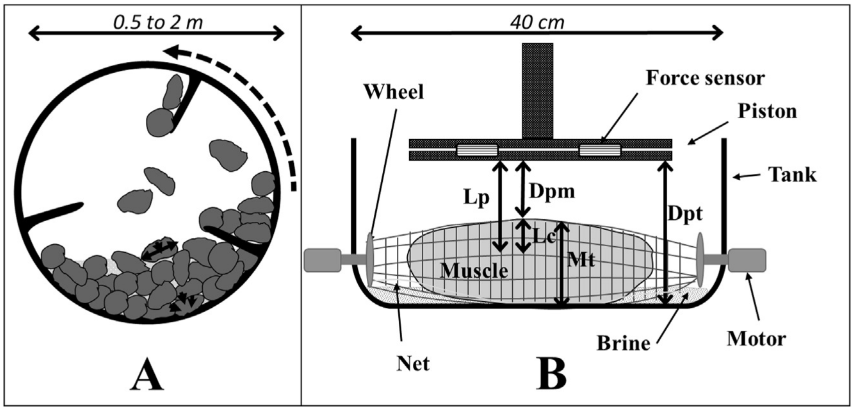

Fig. 1. Sketch of [A] the cross-section of a typical tumbler (black arrows indicate deformation directions) and [B] the tumbling simulator used to control and characterize muscle deformation.