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Setting HACCP Critical Limits for the Precooking CCP of Commercially Processed Tuna

ABSTRACT

Critical Limits (CLs) to prevent histamine formation while processing commercially canned tuna are developed for tuna precooking, using core temperatures and time. The CLs are developed from the thermal death times of *Morganella morganii*, the most heat-resistant of the histaminogenic bacteria in tuna. These CLs will deliver a 5 log reduction of this bacterium and ensure that histamine formation will be sufficiently restricted to allow enough time to continue processing tuna until the finished product is canned and retorted. The US-FDA Seafood HACCP Guide (4th ed) allows an intermediary heating phase Critical Control Point if the total processing time extends over 12 hours. More than 12 hours total processing time is required to process larger tuna fish, thus the need for this CCP and associated CLs. Based on prior work, a critical limit of 60°C for 1 min in the cold spot of the fish has been shown to result in a 5.68 log reduction in *Morganella morganii*. Alternative CLs, using cold-spot core temperature and holding time proposed for a reduction of more than 5 logs, are: 59°C for 2 min (5.41 logs), 58°C for 4 min (5.59 logs), 57°C for 7 min (5.30 logs), and 56°C for 12 min (5.30 logs).

INTRODUCTION

The histamine hazard and seafood HACCP regulations

Annually about 2.5 million tons of wild-caught tuna are processed into commercial canned tuna products worldwide *(15)*. At the processing facilities, tuna are generally processed thawed, i.e., not frozen, and are exposed for considerable periods of time to temperatures at which histamine can form. Histamine, or scombroid toxin, is a heat-stable marine toxin that forms in unchilled or unfrozen tuna *(18)* and can cause scombroid fish poisoning (SFP). What sets the histamine toxin apart from other marine toxins is that its formation is 100% preventable by proper fish handling and processing *(14, 17)*. Histamine is a food safety hazard that harvest vessels and commercial canned

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tuna processors must control to ensure the product is safe for human consumption *(9)*. In the canned tuna industry, most primary processors use a preliminary heat treatment step called precooking *(6)*. The primary reason for precooking is to heat the fish sufficiently so that, when cooled, the edible meat can be easily separated from the red meat, skin and bones before being canned and retorted. Precooking, as the name implies, occurs before the final thermal heating (retorting) process. Precooking requires special consideration and control measures to prevent histamine formation *(9)*.

Seafood products intended for use in the United States must be processed in compliance with the Seafood Hazard Analysis and Critical Control Points (HACCP) regulations in effect since 1997 *(11)* and enforced by the US Food and Drug Administration (FDA). The FDA's Seafood Hazards Guide *(9)* contains parameters and example strategies for: (a) controlling histamine through chilling on board fishing vessels, (b) sampling of incoming fish, and (c) controlling exposure to elevated temperatures at the processing facilities. However, the FDA's guidance currently does not include any parameters or examples for control of histamine formation by use of a thermal process.

Histamine-forming Bacteria

Histamine-forming bacteria (HFB) and their significance to commercial canned tuna processing have been extensively reviewed elsewhere *(6, 7, 27)*. Briefly, HFB produce the enzyme histidine decarboxylase (HDC) which transforms naturally-occurring histidine to histamine *(10)*. The practices, procedures and facilities used by tuna harvesters and processors must protect the raw material and in-process products from the bacterial degradation that results in histamine formation. HFB are susceptible to proper heat treatment; thus, precooking also serves to control histamine formation if sufficient heat is applied to the fish during the precooking step *(9, 27)*. If the fish are not heated sufficiently, the precooking process may not inactivate the HFB, and this failure would then allow an increase in histamine formation at later steps in the process. Therefore, processors must ensure control of the precooking process, because, once it forms, histamine is very heat stable *(9)* and is not destroyed by freezing or high temperature processes, such as retorting.

The Gram-negative bacterium, *Morganella morganii*, is the most histaminogenic of the HFB *(33)* commonly occurring in tuna. Enache et al. *(7)* studied thermal death times (TDT) of five of the HFB species in irradiated tuna loins and also reported that *M. morganii* was the most heat resistant of the HFB. A thermal death study by Enache et al. *(7)* was done in the 50°C to 60°C range, and the kinetics of the model were developed with ca. 6 log CFU/ml of *M. morganii.* In this experiment, bacteria were grown at 30°C, held in an ice bath for inoculation purposes, inoculated onto the tuna, and heated to the various thermal death temperatures; and resulting populations were plated and enumerated after incubation at 26°C to 30°C. Enache et al. *(7)* chose the maximum value in each test to develop the z and D(60) values for the model. It is worth noting that the bacteria grown in albacore loin meat were more heat resistant than those grown in skipjack loin meat *(7)*. The maximum heat resistance values reported by Enache et al. *(7)* for *M. morganii* in albacore tuna are z = 4.1°C and D (60) = 0.26 min. The D-value is the number of minutes at a specific temperature which reduces a population of a specific bacterial organism by 90%, or one log unit (log). The z-value is the number of degrees change that will result in a 10-fold difference in the D-value.

To control histamine formation during processing, both the HDC enzyme and the HFB that synthesize it must be inactivated by the precooking heat process. Since the final precooked product will later be retorted or re-frozen, the precooking treatment must be sufficient to suppress histamine formation long enough for processing of the fish to be finished before they are retorted or refrozen. Kanki et al. *(19)* tested the thermal properties of the HDC enzyme produced by *M. morganii* and found that HDC had the most activity at 40°C, and that the activity was reduced by 50% at 50°C and by 99% at 60°C.

HACCP controls and precooking tuna

Even though commercial tuna processors had been using the precooking step for many decades *(31)*, until very recently there were few scientific data on determining and quantifying the efficacy of the heat treatment in controlling histamine formation in the tuna. To study the inhibitory effect that the precooking step has on histamine formation potential, Vogl et al. *(35)* precooked tuna that had been deliberately allowed to decompose and to accumulate high levels of histamine (in excess of 150 ppm, compared with the FDA's action level of 50 ppm). To spoil the tuna, Vogl et al. *(35)* incubated the whole tuna in flowing seawater that was maintained at 25°C to 33°C to closely match the temperatures chosen by Enache et al. *(7)* and to be in the HFB optimal-growth zone *(9)*. If the water temperature dropped below 25°C at any time, heated seawater was used to adjust it.

In their study, all of the fish Vogl et al. *(35)* tested failed organoleptic testing; these were severely abused fish. The fish used for the experiment had abnormally high bacterial load levels and elevated histamine formation rates that were increasing exponentially prior to precooking. When the batch of test fish was heated to a maximum target core temperature of 60°C, the minimum measured core temperature for any single fish was 51°C, and 50% of the core temperatures on removal from the precooker were 56°C or below. These temperatures are below those that would be determined to deliver a 5 log reduction of *M. morganii*. Even with these core temperatures below 60°C, histamine production was

inhibited in all cases for at least 18 hours after this precooking process ended. The work of Vogl et al. *(35)* validated and supported reported results from Enache et al. *(7)* and validates the values proposed later in this paper.

All the HDC enzyme that had been active before Vogl et al. *(35)* precooked the fish must have been inactivated (i.e., denatured) by precooking because, within 6 hours after they stopped precooking, even though the fish core temperatures were again in the optimal histamine-formation zone, no histamine formed until at least 18 hours. By then, the bacteria populations appear to have regrown (from a depleted state), leading to the production of new HDC enzyme and formation of new histamine. The work of Vogl et al. *(35)* demonstrated the effectiveness of a heat treatment in delaying histamine formation by precooking, a delay allowing sufficient time for completion of processing of the larger tuna.

Commercial tuna processors ultimately achieve control of bacterial pathogens through canning and retorting at the end of the process. However, fish are exposed to conditions that allow histamine to form during processing, prior to being retorted or frozen. Therefore, to prevent histamine formation, the entire process must be controlled. Some facilities have temperature-controlled processing areas where the room temperature is kept low, or the product may be actively cooled at certain steps in the process to help protect it from spoilage; however, even with these controls, processing conditions may allow for histamine formation. FDA guidelines recommend that the time of exposure to unfrozen conditions during processing, including precooking, should be less than 12 hours if the fish is exposed to temperatures exceeding 21°C (70°F) at any point in the process *(9)*. Since the precooking utilizes temperatures that far exceed 21°C (70°F), the 12-hour guideline is in effect and must be adhered to at present, unless special precautions are taken.

Most commercial tuna processing facilities are in tropical regions, so areas around the precookers and the areas for post-precooker fish cooling also tend to exceed 21°C, even outside of the actual precooking process. Smaller tuna can be processed in under 12 hours; however, more than 12 hours are typically needed for processing larger fish. For example, tuna weighing more than 10 kg commonly require at least 24 hours to process from start of thawing through start of retorting *(5)*. Thus, processes such as thawing and precooking just take more time for larger fish.

Based on research by Enache et al. *(7)*, Nolte et al. *(27)* proposed that precooking tuna to 60°C at the cold-point would provide sufficient reduction in histamine-forming potential to allow at least 12 hours of additional safe processing time after the end of the precooking step.

Precooking tuna

The art and science of precooking tuna and the equipment and practices used by commercial processors are described by DeBeer et al. *(6)*. During precooking, the two most important factors that determine the rate of temperature increase are the thickness of the fish, i.e., the distance from the surface of the fish to its core or geometric center, and the temperature differential, or delta T (ΔT), between the surface of the fish and the core. When the core temperature is approaching the bacterium's lethal temperature zone (starting at 50°C) during the precooking cycle, the smallest fish (~0.5 kg) can have a fast heating rate of ~2°C/min at the core of the fish, while larger (thicker) pieces of fish will heat more slowly *(6)*. To optimize processing, the fish are sorted by weight, and the larger fish, e.g., > 10 to 15 kg, are usually cut into smaller portions prior to precooking to reduce yield (moisture) loss due to "overcooking" of the external layers of the fish before the inner portion is fully precooked *(5)*.

Another significant factor impacting precooking time is the initial temperature (IT) of the fish *(6)* when the precooking starts. If the fish has any frozen meat in the core, a substantial amount of extra time and energy is required to thaw the portions that are still frozen before core heating can even start. This is a separate phenomenon from moisture loss through cooking, as moisture loss is more closely correlated with the maximum backbone temperature reached *(2)*. *Figure 1* displays a typical temperature profile of steam and fish in a conventional atmospheric precooker (CAP). The time it takes for the heat to pass through the flesh to the core, before the core temperature starts to increase, is called the lag time. Note the different lag times of the different fish and how the core temperatures continue to increase (change), even after the steam is turned off. This variation is expected and normal, even if the fish are properly sized *(6)*.

Precooking equipment

Processors precook the tuna in batches on multi-layered oven racks that are rolled into the precookers. The vast majority of precookers currently used in the world are either CAPs or vacuum precookers (VPCs) *(24, 26)*. CAPs generally precook with saturated steam at an ambient temperature of ~100°C, and the precooking ambient temperature is held at 100°C by adding steam, as needed, during the process. Since the precooker steam bleeders and drains remain open during processing, the internal pressure remains close to atmospheric pressure *(26)*.

VPCs control the precooking temperature by controlling both the ambient pressure and ambient steam temperature in a special vacuum chamber through the use of steam, vacuum pumps, and water sprays on the precooker shell to cool the shell; see *Fig. 2* for an ambient steam profile for a VPC. The lag phase in a VPC is at least as long as the lag phase in a CAP *(24)*, depending on fish size and initial core temperatures. The heating rates are generally slower for the same size fish, and, toward the end of the heating cycle, the core temperatures may be more uniform than in a CAP *(24)*.

Most precooking cycles in a VPC feature a step-down steam temperature profile in which the steam temperature

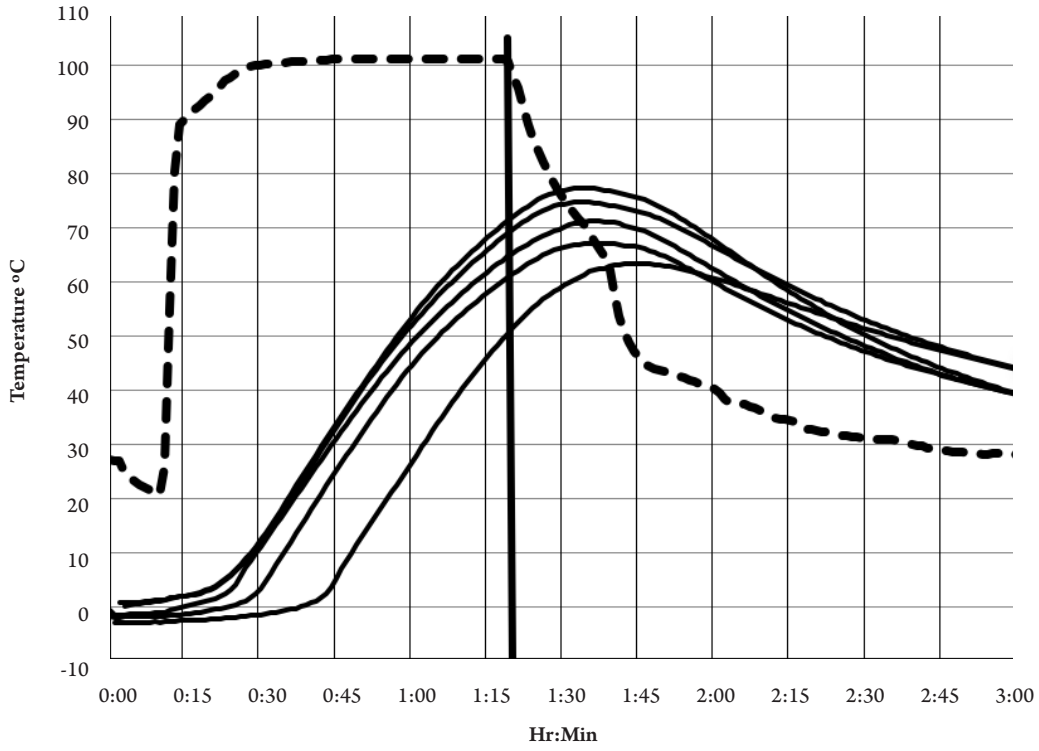

Figure 1. Temperature profile of a conventional atmospheric precooker (CAP)

Broken line is ambient steam temperature. Solid lines represent the backbone temperatures of individual 1.8 to 2.7 kg tuna. Heavy vertical line indicates when steam is turned off.

is reduced, or "stepped down," from, for example, 100°C to 70°C, in a timed series of steps during the process *(36)*. This step-down method in precooking steam temperature is meant to help reduce yield losses due to overcooking the outer portions of the fish before the inner portion is fully cooked *(24)*.

One of the effects of precooking is that the interior of the fish will continue to heat up after the steam has been turned off *(6)*; see *Fig. 1*. The difference in temperature from the surface of the fish to the core is defined as the delta T (ΔT). When the steam is turned off in a CAP with a steam temperature of 100°C, there will be a greater ΔT between the outer surface of the fish and the core than will occur in a VPC that finishes the precooking process at a steam temperature of 70°C or 80°C. For example, if the steam temperature is 100°C in a CAP, and the steam is turned off when the core temperature of the fish is at 55°C, the ΔT is 45°C. This process will passively continue to drive a further increase in core temperature. This is in contrast to the situation in a VPC, with a final process target ambient steam temperature of 70°C and a fish core temperature of 55°C, where there is a ΔT of just 15°C. Therefore, the rate and amount of post steam-off core temperature increase is much greater for fish processed in a CAP than for those processed in a VPC, with these conditions and temperature parameters. This knowledge can be used when processors are designing their precooking processes to determine when to stop the precooking process and start cooling the fish *(26)*.

After the fish have been precooked, processors will try to cool the fish as quickly as possible to stop the loss of moisture (due to overcooking) and thus optimize yield *(6)*. Some operators who use CAPs may stop the precooking process with a water spray inside the precooker after turning off the steam *(24)*, but in most facilities that use CAPs, the water spray cooling is done after the fish is outside the precooker *(24)*. In facilities that use VPCs, the fish may start cooling while still inside the precooker. The VPC is designed to cool the fish rapidly using evaporative cooling procedures and engineering controls *(30, 36)*; see *Fig. 2*. The center of the fish starts cooling quite quickly and thus leaves less time for the core temperature to increase passively, since the ΔT decreases quite quickly. An effective precooker critical limit (CL) monitoring strategy of histamine control for VPCs and CAPs needs to deal with the particular steam precooking and cooling profile(s) being used *(26)*.

Establishing the critical limits for the precooking CCP

Numerous researchers *(13, 16, 20, 21, 22, 23, 28, 32)* have reported on the initial loads of HFB found in tuna and other fishes. Some have reported no HFB, some have reported less

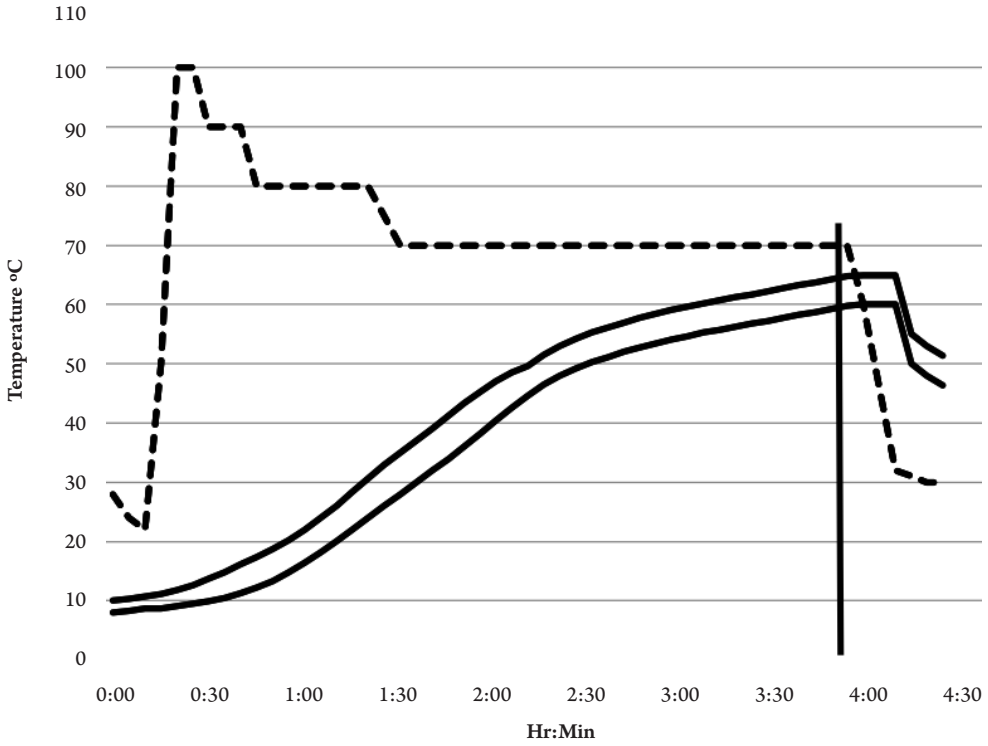

Figure 2. Temperature profile of a vacuum precooker (VPC)

Broken line is ambient steam temperature. Solid lines represent the backbone temperature of individual tuna. Heavy vertical line indicates when steam is turned off.

than a maximum of 10^2 CFU/g, and one *(13)* reported an average of 3.5×10^3 CFU/g adjusted to a maximum of 1×10^4 CFU/g. A summary of the initial loads of HFB is shown in Appendix A.

Targeting a 5 log reduction of the most heat resistant pathogenic bacteria is in line with other processes that use heat treatment to reduce the bacterial load in other foods. For example, almond processors target a 4 or 5 log CFU/g reduction *(1)*, juice processors target a 5 log CFU/ml reduction *(8)*, and processors of meat products *(34)* target bacterial reduction goals of 5 log to 7 log CFU/g. The Canadian Food Inspection Agency (CFIA) also specifies a 5 log CFU/g reduction of *Listeria monocytogenes* for ready-to-eat (RTE) seafood *(4)*. In fact, all of the heat treatments cited above are for RTE foods, not foods that will later be subjected to another severe heat treatment, such as retorting.

In this manuscript, the CL is the minimum internal core temperature for any of the individual fish sampled, unless otherwise noted. How the minimum individual values are applied to a batch of precooked fish will be addressed later by: (a) risk-based sampling and (b) practical applications for using these CLs for the precooking CCP.

For the precooking CCP, the CLs are temperatures of the core of the tuna and times (minutes of exposure) that achieve a 5 log CFU/g reduction of *M. morganii*. Various temperature and time CLs scenarios could make this reduction possible. Examples of alternative CLs for pathogen control are given in the FDA's Seafood HACCP Guide *(Appendix 4, Tables A-3 and A-4)* *(9)*.

In summary, because there is now sufficient experimental evidence that precooking serves to suppress histamine formation for a sufficient period of time to allow processors to completely and safely process even the largest fish, we propose the development of specific CL goals.

OBJECTIVES

The objectives of this paper are to:

1. Develop CLs using minimum product core temperatures and holding times that achieve a minimum of a 5 log CFU/g reduction of *M. morganii*, thereby eliminating histamine formation for a sufficient time period for the fish to be fully processed.
2. Build on the work by Nolte et al *(27)* developing different log-lethality tables, using published techniques *(29)* to calculate and report when an accumulated 5 log CFU/g bacterial reduction of *M. morganii* has been achieved. The tables will be based on the core temperature lower limit on the same fish batch at two different times.

3. Develop some simple guidelines to demonstrate to the precooker operator how to use log-lethality tables to achieve a safe and effective process.

METHODS AND MATERIALS

Using the z and D*(60)* values from work done by Enache et al. *(7)*, the accumulated log lethality was calculated for different product core temperatures, assumed heating rates, and minimum holding times. The lethal rate (L) is calculated as $L = 10^{[(T-60)/z]}$ using the General Method developed by Bigelow et al. *(3)*. The log reduction is equal to the lethal rate (L) divided by the D(60). The log reduction calculations were based on Patashnik's method of using the Trapezoidal Rule of averaging the lethalities of two adjacent temperatures to the temperature of each time interval *(29)*. The accumulated D is the cumulative sum of the log reductions by time period (minutes). To understand the time-temperature lethality rates of *M. morganii* occurring during precooking, scenarios were constructed using different temperatures, times, and heating rates. These scenarios are:

1. Scenarios 1, 2, and 3: Different linear heating rates of 2°C, 1°C, and 0.5°C per minute at the core were used, starting with a 50°C core temperature to determine the accumulated log lethality.
2. Scenario 4: Temperatures were held at a fixed time in the bacterium's lethal zone for an extended time period after a very fast heating rate of 2°C per minute *(27)*: the accumulated log reduction in lethality was calculated on the basis of starting at 50°C or 51°C. Very little log lethality is accumulated at these starting temperatures, so they were chosen for calculation convenience.
3. Scenarios 5, 6, and 7: The increases in accumulated log reductions for changing product core temperatures were measured at time intervals of 5, 10 and 15 minutes. In these scenarios, the log lethality rate per minute is automatically included for the accumulated log reduction. A very fast heating rate of 2°C per minute increase in core temperatures was used to reach the starting core temperature; this heating rate allows for little accumulation of log lethality before the hold intervals start.

RESULTS

Results for Scenarios 1 to 3 are charted in both *Figs. 3 and 4.* The accumulated log lethality versus core temperature for the three different heating rates is plotted in *Fig. 3*, and the accumulated log lethality versus time for the same three different heating rates is plotted in *Fig. 4.* The difference in

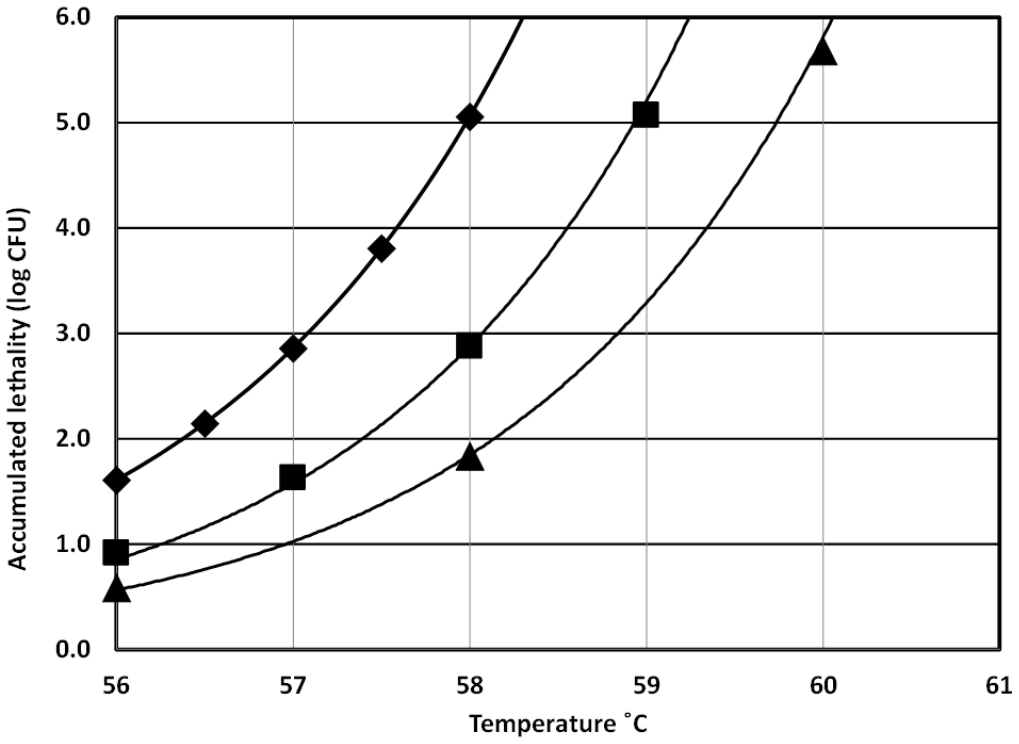

Figure 3. Accumulated log lethality of **Morganella morganii** *with different core temperature heating rates starting at 50°C*

Diamonds (0.5°C/min), Squares (1°C/min), Triangles (2°C/min).
Data from Scenarios 1, 2 and 3.

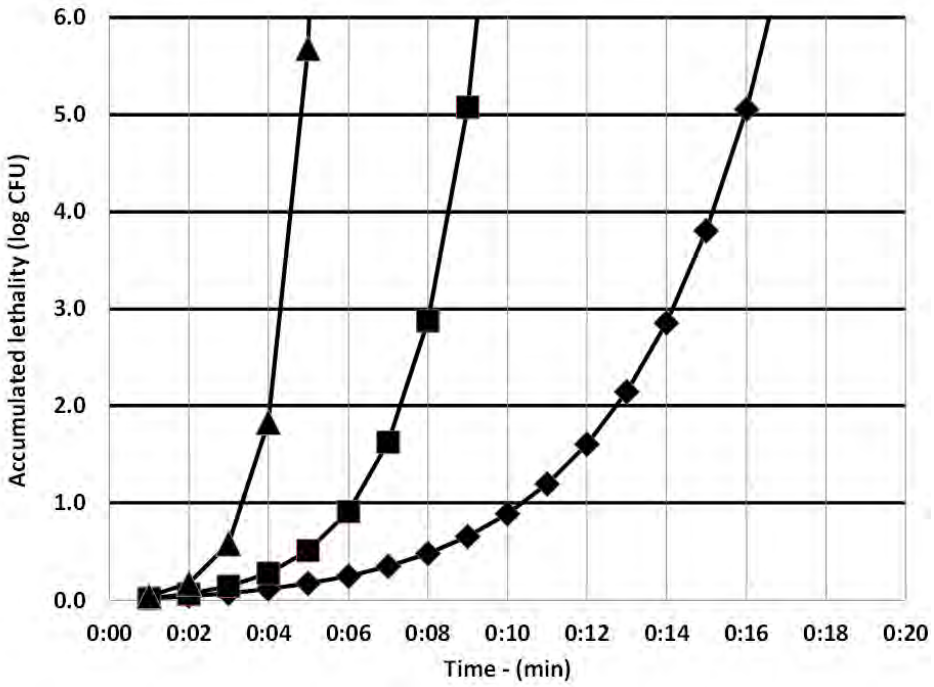

Figure 4. Minutes to achieve accumulated log lethality of **Morganella morganii** *with different core temperature heating rates starting at 50°C.*

Triangles (2°C/min), Squares (1°C/min), Diamonds (0.5°C/min).
Data from Scenarios 1, 2 and 3.

accumulated log reduction at different core temperatures in *Fig. 3* is the result of the difference in heating rates per minute. The difference in accumulated log reduction in *Fig. 4* is the result of the difference of time accumulation depending on the heating rates. The targeted 5 log lethality is reached at lower temperatures but with longer precooking times when heating rates are slower, because of the longer time spent at lethal temperatures *(Fig. 4)*. The figures together clearly demonstrate the impact of different heating rates on the amount of log lethality that is accumulated over time.

The accumulated log lethality when the core temperature remains fixed for a period of time is shown in *Table 1*. A very fast heating rate of 2°C/min starting at 50°C was used to get to the indicated core temperature, which was then held fixed for 1–13 minutes. This fast initial internal (core) heating rate is a conservative treatment (does not allow for significant accumulated log reduction before the subsequent holding period) and would normally occur only in very small tuna *(27)*. Note that each of the following temperature-time combinations achieve the same result (a more than 5 log reduction). With a core temperature fixed at:

- 60°C and held for 1 min there is an accumulated log lethality of 5.68,
- 58°C and held for 4 min there is an accumulated log lethality of 5.59, and
- 56°C and held for 12 min there is an accumulated log lethality of 5.06.

It is fairly simple to construct tables with accumulated log lethalities over time between any two sets of product core temperatures. The strategy proposed here is conservative because it does NOT account for any additional lethality during cooling outside of the precooker, although additional lethality does, in fact, occur during the cooling as long as the temperature remains within the lethal zone. Not counting the lethality in the cooling phase is very much in line with Frazier's *(12)* recommendations for monitoring heat processing under HACCP guidelines.

The increase of accumulated log lethality as the post steam-off core temperatures increase or stay the same between the two time intervals is shown in *Tables 2, 3, and 4. Table 2* shows the lethality values for a 5-minute interval, *Table 3* for a 10-minute interval, and *Table 4* for a 15-minute interval.

For example, if the core temperature is 55°C at time zero (T-0) and 60°C after 5 minutes (T-5) in the same individual fish, the accumulated log lethality is 8.6 *(Table 2)*. But if the core temperature is 55°C at time zero (T-0) and 58°C after 10 minutes (T-10), the accumulated log lethality is 6.8 *(Table 3)*. And if the core temperature is 55°C at T-0 and 57°C after 15 minutes (T-15), the accumulated log lethality is 6.9 *(Table 4)*.

TABLE 1. Accumulated log reduction of *Morganella morganii* based on holding at a fixed temperature after a 2˚C/min heating rate

	Time in minutes at a fixed temperature (°C)								
Minimum core temperature	1 min	2 min	3 min	4 min	5 min	7 min	8 min	12 min	13 min
60°C	5.68	9.53	13.37	17.22	21.06	28.76	32.60	47.99	51.83
59°C		5.41	7.60	9.79	11.99	16.37	18.57	27.34	29.54
58°C				5.59	6.84	9.34	10.59	15.59	16.84
57°C						5.30	6.01	8.87	9.58
56°C								5.06	5.46

Based on a z = 4.1°C and D(60) = 0.26 min using the Trapezoidal Rule and starting at either 50°C or 51°C.
Data from scenario 4.

TABLE 2. Accumulated log reduction of *Morganella morganii* after waiting 5 minutes to re-measure the core temperature

	Final Minimum Core Temperature		
Initial Minimum Core Temperature	60°C	59°C	58°C
60°C	**23.1**, (0.0)		
59°C	**17.7**, (0.2)	**13.2**, (0.0)	
58°C	**14.1**, (0.4)	**10.1**, (0.2)	**7.5**, (0.0)
57°C	**11.7**, (0.6)	**8.1**, (0.4)	**5.8**, (0.2)
56°C	**9.9**, (0.8)	**6.7**, (0.6)	
55°C	**8.6**, (1.0)		
54°C	**7.7**, (1.2)		
53°C	**7.0**, (1.4)		

Based on a z = 4.1°C and D(60) = 0.26 min using the Trapezoidal Rule, starting at either 50°C or 51°C.
Numbers in parentheses (heating rates °C/min for interval).

DISCUSSION

With the data tables provided, it is possible to understand how many log reductions for *M. morganii* one can achieve during precooking, and thus how much lethality the precooking process can, in fact, provide. If the chosen safety objective is a 5 log reduction of *M. morganii*, these tables would allow an operator to determine when the target is achieved. In fact, because the operator is trying to achieve a minimum of 5 log reduction of *M. morganii* and while also trying to avoid overcooking so as to preserve yield and the quality attributes of the fish, in most cases at the end of the heating operation there will already be well over a 5 log reduction cycle at the core or geometric center of the fish piece. Because the outside of the fish and the gill area get more heat than the core, those areas will have had considerably higher accumulated log lethality.

Figures 3 and 4 show how quickly log lethality can accumulate during precooking and *Tables 2, 3, and 4* also indicate how quickly lethality can accumulate from longer exposure to passive heat after precooking. This additional *M. morganii* lethality is not necessarily an indicator of overcooking, since cook values are normally associated with much higher z-values *(26)*. The data also indicate that when the core temperature slowly approaches 60°C, the accumulated log reduction increases rapidly with either every degree increase and/or every minute: see *Fig. 3 and 4*. An

TABLE 3. Accumulated log reduction of *Morganella morganii* after waiting 10 minutes to re-measure the core temperature

	Final Minimum Core Temperature			
Initial Minimum Core Temperature	60°C	59°C	58°C	57°C
60°C	**42.3**, (0.0)			
59°C	**32.5**, (0.1)	**24.1**, (0.0)		
58°C	**25.7**, (0.2)	**18.5**, (0.1)	**13.8**, (0.0)	
57°C	**20.9**, (0.3)	**14.6**, (0.2)	**10.6**, (0.1)	**7.8**, (0.0)
56°C	**17.5**, (0.4)	**11.9**, (0.3)	**8.4**, (0.2)	**6.0**, (0.1)
55°C	**15.0**, (0.5)	**10.0**, (0.4)	**6.8**, (0.3)	
54°C	**13.1**, (0.6)	**8.6**, (0.5)	**5.7**, (0.4)	
53°C	**11.7**, (0.7)	**7.5**, (0.6)		
52°C	**10.6**, (0.8)	**6.7**, (0.7)		
51°C	**9.7**, (0.9)	**6.0**, (0.8)		
50°C	**8.9**, (1.0)	**5.5**, (0.9)		

Based on a z = 4.1°C and D(60) = 0.26 min using the Trapezoidal Rule, starting at either 50°C or 51°C.
Numbers in parentheses (heating rates °C/min for interval).

TABLE 4. Accumulated log reduction of *Morganella morganii* after waiting 15 minutes to re-measure the core temperature

	Final Minimum Core Temperature				
Initial Minimum Core Temperature	60°C	59°C	58°C	57°C	56°C
60°C	**61.5**, (0.0)				
59°C	**47.2**, (0.7)	**35.1**, (0.0)			
58°C	**37.2**, (0.13)	**26.9**, (0.07)	**20.0**, (0.0)		
57°C	**30.2**, (0.20)	**21.2**, (0.13)	**15.4**, (0.07)	**11.4**, (0)	
56°C	**25.1**, (0.27)	**17.2**, (0.20)	**12.1**, (0.13)	**8.8**, (0.07)	**6.5**, (0.0)
55°C	**21.4**, (0.33)	**14.3**, (0.27)	**9.8**, (0.20)	**6.9**, (0.13)	
54°C	**18.6**, (0.40)	**12.2**, (0.33)	**8.2**, (0.27)	**5.6**, (0.20)	
53°C	**16.5**, (0.47)	**10.6**, (0.40)	**7.0**, (0.33)		
52°C	**14.7**, (0.53)	**9.4**, (0.47)	**6.0**, (0.40)		
51°C	**13.4**, (0.60)	**8.4**, (0.53)	**5.3**, (0.47)		
50°C	**12.3**, (0.67)	**7.6**, (0.60)			

Based on a z = 4.1°C and D(60) = 0.26 min, using the Trapezoidal Rule.
Numbers in parentheses (heating rates °C/min for interval).

TABLE 5. Accumulated log reduction of *Morganella morganii* based on holding at a fixed temperature after a 2°C/min heating rate

Minimum Core Temperatures	Elapsed Time	Reduction log (CFU)
60°C	1 min	5.68
59°C	2 min	5.41
58°C	4 min	5.59
57°C	7 min	5.30
56°C	12 min	5.06

Adapted from Table 1.

Based on a z = 4.1°C and D(60) = 0.26 min, using the Trapezoidal Rule.

Based on a 2°C/min heating rate and then holding at a fixed temperature.

application of more than a 5 log heat process is just a waste of heat and resources if the goal is to achieve product safety, although some processors may choose to do so to produce different fish textures.

In the 4th scenario, shown in *Table 1*, the fish were heated quickly and then held at a constant temperature. This process is similar to a vacuum precooker cycle, in which the fish is precooked in a step-down process. For example, if the fish are heated until the cores are 57°C and then held for seven minutes, or heated to 58°C and then held for four minutes, or held at 59°C core temperature for two minutes, more than a 5 log lethality reduction is achieved in all cases. The automatic controller of VPCs can be programmed with specific precooking regimes like these that ensure the minimum CLs are achieved.

Using minimum core temperatures to monitor precooking CLs will require adherence to a series of prerequisites detailed in the Canned Tuna HACCP Guide *(25)*. A key concept for making preparations for precooking is to keep things uniform: uniform sizing, uniform thawing, uniform splitting, and uniform racking. Properly thawing uniformly sized fish before precooking saves a tremendous amount of steam because the fish are not being thawed in the precooker. If all of the fish in a batch pass through the initial temperature lag phase *(Fig. 1)* at the same rate and time, the end point temperatures in all fish will be very close to one another, provided there is good temperature distribution throughout the precooker. It will also help processors to determine whether the fish in the batch have been cooked enough to have reached a 5 log reduction in lethality.

At the start of precooking, the increase in tuna core temperature follows a certain pattern. There is an initial lag of temperature increase as the heat moves towards the geometric center of the fish or piece of fish *(6)*; *Fig. 1*. Once this lag phase has passed, the rate of temperature increase is relatively uniform for the size of the fish, the type of precooker, and ambient temperature. Note, from *Fig. 1*, the variation in the core temperature when the steam is turned off or at the maximum core temperature depends on how long the core temperatures remain in the lag phase. A practical monitoring procedure to measure this variation for each type of precooking, CAP or VPC, the topic of a future paper by the authors.

In a CAP, after the steam is turned off *(6)*, the tuna core temperatures continue to increase over a period of several minutes *(Fig. 1)*. Since in a tuna factory, most precooking heating profiles do not achieve a heating rate of exactly 1°C or 0.5°C per minute *(6)*, another more practical approach was developed to determine the accumulated log lethality by simply sampling the core temperature from the same fish at two different times. Smaller fish will start cooling faster than larger fish, so the temperatures need to be collected and analyzed promptly.

If the fish temperatures are measured during the time when the core continues to heat after the steam has been turned off, but the fish have not achieved a 5 log lethality when the first core temperature measurement is collected, the core temperatures can be remeasured after 5, 10, or 15 minutes. So, for the simplest example, if all the fish have been removed from the precookers and all of the fish in the sample have core temperatures over 60°C, the operators can be certain the 5 log reduction of *M. morganii* was reached. But if core temperatures had not reached that goal but were over 56°C, the operator can wait, since the core temperature continues to increase for some time. If the core temperature is 56°C and the operator waits 5 minutes before re-measuring, and if the core temperature measures 60°C, the operator can be confident that the log reduction is much greater than 5 log, based on data in *Table 2*. If the core temperature starts at 56°C and after 5 minutes is only 58°C, the 5 log reduction has not yet occurred, based on data in *Table 2*. If the operator now waits another 5 minutes, and the temperature is still 58°C, then there is almost an 8.4 log reduction of lethality at the core, based on *Table 3*.

A more conservative way of measuring the elapsed time between measurement cycles is to start the 5 or 10 or 15 min periods from when the last fish was measured. For example, if the team measures the temperature with 24 thermometers, and the 1st round of 24 measurements was from 08:02 to 08:08, the 5/10/15 minute waits start from the 08:08 mark. So the next measurements will be at 08:13 (5 min wait), 08:18 (10 min wait), and 08:23 (15 min wait).

CONCLUSIONS

The primary CL of a tuna precooking cycle should be a 60°C minimum core temperature at the first measurement *(27)* requiring no additional time or measurements. The authors suggest that any batches with exit core temperatures lower than 56°C should be returned to the precooker for further heating. The 56°C is suggested because it is only 1 z-value below 60°C, and the additional heating time to achieve a 5 log reduction should be relatively short. But if any core temperature(s) are between 56°C and 60°C, the operator would just have to wait and remeasure the temperature(s). After the core temperatures are measured and verified, or remeasured and verified, the fish should be cooled as quickly as possible to minimize moisture loss and preserve the quality attributes.

Critical limits for the precooking critical control point can be established by taking into account the desired log reductions of *M. morganii* and the following considerations:

1. Where monitoring of core temperature over time is practical during precooking and has been validated (such as in a VPC), critical limits can be established based on continuous measurement of core temperatures, as shown in *Tables 1 and 5*.
2. Otherwise, where measurements of core temperature at two different times are practical, core temperature critical limits can be established using the wait times of *Tables 2, 3, or 4*.
3. Additionally, in special cases, a VPC with a computer controller may be programmed by the manufacturer to achieve a 5 log reduction in *M. morganii* by General Method calculation, as determined by a thermal process authority and provided that all equipment, instruments, and processes are validated as outlined in the NFI HACCP Guidelines *(25)* and the 2011 FDA's Seafood HACCP Guide *(9)*.
4. Finally, processors wishing to minimize moisture loss due to precooking should attempt to do so by targeting the lowest possible minimum core temperatures for all the fish, while ensuring that the critical limit for histamine control is met.

Precooking tuna to a suitable core temperature can be regarded as a robust and valid system for preventing histamine formation during the routine processing of traditional canned tuna. Historically, the minimum core temperature of 57.3°C (135°F) for precooking tuna proposed by Peterson *(31)* in the early 1970s has been the de facto standard for almost 50 years. In retrospect, having reviewed the precooking process by use of recent information, i.e., Enache et al. *(7)* and Vogl et al. *(35)*, Peterson's minimum core temperature target was quite good; when the fish are precooked in CAPs to the target suggested by Peterson, the necessary lethality is achieved because the core temperatures continue to increase during the time the fish are removed from the precooker, but before they have started to cool. Since fish core temperatures proposed here as CLs have been shown to be very close to the historical backbone (core) or geometric center fish temperature targets, this indicates how robust the precooking system has been over the years in controlling histamine formation. The important research by Enache et al. *(7)* and Vogl et al. *(35)* confirmed how robust the precooking operation is. We have shown how to use this information to develop alternative CLs for the precooking CCP in order to prevent further histamine formation, so that the processing of canned tuna has at least 12 extra hours after precooking.

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APPENDIX A

Populations of Histamine-forming Bacteria in Good Fish			
Author – year	**Species**	**Max CFU/gm**	**Brief summary**
1983 – Taylor and Speckhard *(32)*	Skipjack tuna *(Katsuwonus pelamis)*	Not measured	Only 3 out of 10 fish had any histamine-forming bacteria on them.
1983 – Okuzumi et al. *(28)*	Skipjack tuna *(Katsuwonus pelamis)*	Not detected	Study in the Sea of Japan for histamine-forming bacteria. None reported for skipjack.
1994 – Lopez-Sabater et al. *(23)*	Bluefin *(Thunnus thynnus)*	1.1×10^3 CFU/gm	Histamine-producing bacteria counts between 4 CFU/gm and 1.1×10^3 CFU/gm were only found in three samples from the last step of the canning process before heat sterilization. In fact, post-catching contamination has been considered.
1996 – Lopez-Sabater et al. *(22)*	Bluefin *(Thunnus thynnus)*	1.1×10^1 CFU/gm	Tuna was gutted and chopped up. Very low numbers of HFB. *Enterobacteriaceae* counts < 10^3 CFU/gm, fish from retail markets in Spain.
2011 – Koohdar et al. *(21)*	Skipjack tuna *(Katsuwonus pelamis)*	10^3 CFU/gm, Histamine	Oman Sea, histamines near 200 ppm, but HFB at 10^3 CFU/gm – The authors did not even use log numbers on the Y-axis for CFU/gm count.
		10^2 CFU/gm, low histamines	Histamines under 50 ppm, HFB at almost 10^2 CFU/gm levels.
2013 – Garcia-Tapia et al. *(13)*	Yellowfin *(Thunnus albacares)*	10^4 CFU/gm – adjusted	Mexico - mesophilic HFB – 10^4 CFU/gm, histamine at 40 ppm, HFB 5×10^3 CFU/gm, (SD - 2.3×10^3).
2012 – Koohdar et al. *(20)*	Longtail tuna *(Thunnus tonggol)*	3×10^3 CFU/gm, Table 2	Histamines over 50 ppm, but HFB at 10^3 CFU/gm – The authors did not even use log numbers on the Y-axis for CFU/gm count.
			Histamines under 50 ppm, HFB at almost 200 CFU/gm levels.
2015 – Hongpattaraker et al. *(16)*	Longtail tuna *(Thunnus tonggol)*	1×10^3 CFU/gm	Thailand – fresh fish, max Initial viable count at 10^3 CFU/gm, histamine max at 11 ppm.