

5

Warming of Cadaveric Specimens

Kelly B. Kennett
Jeff R. Crandall
Walter D. Pilkey

Automobile Safety Laboratory
Department of Mechanical, Aerospace, and Nuclear Engineering
University of Virginia
Charlottesville, VA

Paper was presented at the 22nd Annual Workshop on Human Subjects for Biomechanical Research. This paper has not been screened for accuracy nor refereed by any body of scientific peers and should not be referenced in the open literature.

Warming of Cadaveric Specimens

Kelly B. Kennett
Jeff R. Crandall
Walter D. Pilkey

Automobile Safety Laboratory
Department of Mechanical, Aerospace, and Nuclear Engineering
University of Virginia
Charlottesville, VA

Abstract

No standard time period exists for the warming of refrigerated cadavers prior to impact testing. Variations in body temperature among dynamic tests, due to unregulated warming practices, can result in significant differences in tissue properties and consequently, injury patterns. In order to investigate the length of time required for a subject to warm to ambient temperature, thermocouples were placed in the right femoral and carotid artery of nine refrigerated, embalmed cadavers. Data recorded from these temperature probes indicates that refrigerated cadavers have substantially different warming times, depending on their overall mass and physical build. Newton's Law of Cooling is used to analyze the data and predict the warming time for any cadaver, given the subject's storage temperature, height, weight, and the ambient temperature.

Introduction

The mechanical properties of human tissues, particularly soft tissue, can vary significantly with decreased temperature from their *in vivo* state. Many human subjects are refrigerated or frozen for storage while awaiting use as a surrogate in impact testing. In order to eliminate the

confounding effects of decreased body temperature on dynamic response, cadavers should be warmed to a temperature close to metabolic temperature. As heating of cadavers is prohibitively cumbersome and impractical, subjects should be allowed to fully achieve at least ambient room temperature in order to maintain a biofidelic test response. Currently, no standard time period exists for the warming of refrigerated cadavers prior to impact testing. This paper describes the development of a function to predict the warming time of a refrigerated cadaver, using empirical data from the warming of nine refrigerated, embalmed cadavers at the University of Virginia's Automobile Safety Laboratory.

Background

The human cadaver as a whole becomes stiffer, with greater viscous and plastic response, as body temperature is decreased over the range of interest (0-20 °C) for refrigerated subjects. This response change is due to changes in the mechanical properties of soft tissues and fluids, as well as the altered interactions of the body's tissues due to thermal contraction at decreased temperatures.

The elastic constants of bone vary inversely with temperature. The coefficient for the change in the modulus of elasticity

for bone due to temperature changes has been reported in the range -0.17% /°C to -0.24% /°C (Ashman, Donofrio, et al., 1982; Yoon and Katz, 1976; Bonfield and Tully, 1982). Over the temperature range of interest for refrigerated cadavers, the elastic moduli of bone vary approximately 4%. This variance, however, is negligible compared with that of soft tissue.

The soft tissues of central interest to joint flexibility and range of motion are tendons and ligaments. Much of the research on tendon and ligament properties has been performed on small mammal tissues and generalized to human tissue. Viidik and Lewin (1966) found that ligament stiffness in rabbits increases 30% as tissue temperature falls from 20 °C to 4 °C. Permanent elongation was found to result from even low anatomical loads applied to rat tendons at decreased temperatures (Warren, Lehmann, and Koblanski, 1976). Thermal contraction of rabbit ligaments causes a baseline shift in the force-deflection curves. The initial position (i.e., length) of the ligament was found by Lam, Thomas, et al. (1990) to be the determining factor in the zero location for monotonic loading. Concurrently, the hysteresis energy of ligamentous tissues increases as temperature decreases (Woo, Lee, et al.). The low temperature conditions cause joints to become inflexible over the normal anatomical range of motion.

The differences in thermal expansion response of the body's various tissues causes non-biofidelic stresses in the body at lower temperatures due to the dissimilar contractions of the tissues. The cubical expansion coefficient of fat is approximately 20 times that of bone and five times that of muscle (Duck, 1990). Thus, the geometrical relationships of the organs are altered at decreased temperatures.

With the vastly varying characteristics of soft tissue over the temperature range of interest, as well as the altered tissue volumes and stresses within the body due to nonuniform thermal contractions, biomechanical response of the subject will differ with body temperature. Clearly, metabolic temperature is ideal for biofidelic response; however, heating the subject to *in vivo* temperature, and maintaining that level until test time, is impractical. Moreover, the rate of decomposition of the subject increases at higher temperatures. Excessive tissue degradation from periods of elevated body temperature will also harm the biofidelic response of the subject. With these considerations in mind, ambient room temperature is the choice for subject temperature during impact tests. It is therefore necessary to standardize the warming time for cadaveric subjects in order to ensure the subject's temperature has reached the ambient room level, thereby eliminating dynamic response differences due to temperature from the impact test data bases.

Test Methods

In order to investigate the length of time to required for a subject removed from refrigeration to reach ambient temperature, thermocouples were installed through the right common carotid and right femoral arteries of cadavers being prepared for impact testing. One thermocouple probe was inserted into the aortic arch area via the common carotid artery in the neck. The other probe was inserted into the upper abdomen just inferior to the diaphragm via the femoral artery. As the abdomen and thorax, or 'core', of the body was the last to warm, no extremity or head data were taken.

Probes were inserted into the subjects prior to removal from the refrigerator in order to allow the probes and the surrounding tissue to equilibrate to the refrigerated temperature. Two probes monitored the ambient temperature. The cadaver was then placed supine, arms at the sides, in a plastic shroud on a hospital gurney. The room's ambient temperature was regulated to 20-23 °C. Data were taken every two minutes simultaneously from all four probes. The probes were removed between three and four days after insertion, just before impact testing of the subjects. Data samples for each probe were averaged over 16 minute intervals to smooth the temperature vs. time plots. Figure 1 shows a representative time/temperature plot.

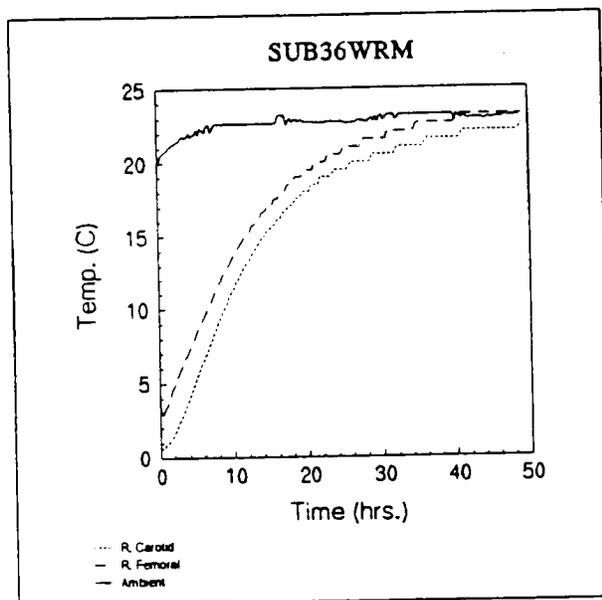


Figure 1. Typical temperature vs. time plot.

Analysis

An analytical function is sought to describe the warming of the cadavers. Marshall and Hoare in the early 1960's laid the ground work in forensic science for the determination of time of death from cadaver

cooling data (Marshall and Hoare, 1962). Temperature data was taken from 1 to 24 hours postmortem. Marshall and Hoare found that the cooling of cadavers followed Newton's Law of Cooling after approximately 12 hours postmortem. In the first twelve hours after death, the cooling data followed Newton's Law if it was modified with terms to account for postmortem metabolism and the non-uniform establishment of temperature gradients. It was therefore hypothesized that the warming of long-term postmortem cadavers would follow Newton's Law exactly with only a sign change of the coefficient. Equation (1) presents Newton's Law of Cooling.

$$\frac{ms}{A \cdot \epsilon} \frac{d\theta}{dt} = -\theta \quad (1)$$

where $\theta = T_{\text{ambient}} - T(t)$, m = mass, s = specific heat, A_e = effective radiating area, and ϵ = emissivity.

The specific heat and emissivity for the human were considered to be constant; therefore, $k = \epsilon/s$. The surface area of the body is difficult to measure directly. The best formula to date for predicting the body's surface area from easily measurable parameters was published by DuBois and DuBois (1961). Equation (2) is the DuBois formula relating height (H) and mass (M) empirically to surface area (A). Height is in centimeters and mass is in kilograms.

$$A = 71.84 \cdot M^{0.425} \cdot H^{0.725} \quad (2)$$

With the body lying supine with arms at the sides ('mummy' position), the entire surface is not the radiating area. Hardy and DuBois (1938) found $A_e = 0.8 A$ for the mummy position. The anthropomorphic constants are grouped into the Size Factor. $S.F. = A_e/m$. Finally, all the constants are grouped into one variable, Z (Equation (3)).

$$Z = (k \cdot S.F.) \cdot 10^{-3} \quad (3)$$

Newton's Law of Cooling can then be written in terms of just one constant, (Equation (4)). This expression can then be solved to find Equation (5). T_{ambient} is considered to be a constant.

$$\frac{1}{Z \cdot 10^{-3}} \frac{d\theta}{dt} = -\theta \quad (4)$$

$$\ln(\theta) = -Z \cdot 10^{-3} t + c \quad (5)$$

$$c = \ln(T_{\text{ambient}} - T_0)$$

Results

The data collected for each subject were plotted linearly on a $\ln \theta$ vs. time graph. A closest-fit linear regression line can then be found. Figure 2 shows the $\ln \theta$ vs. time plot and the regression fit for the same data shown in Figure 1.

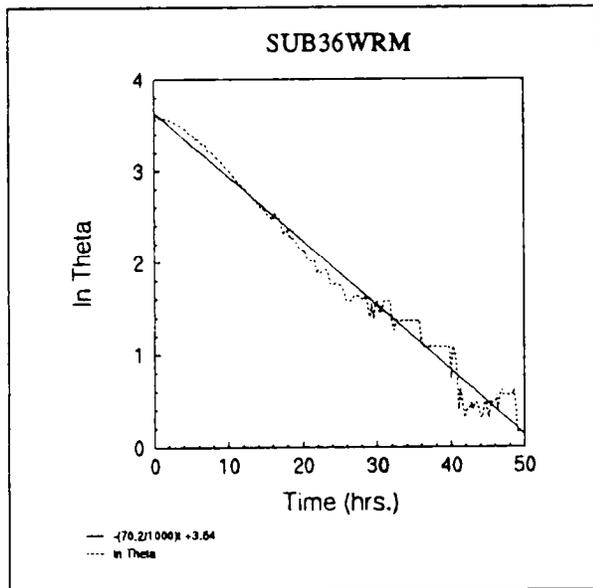


Figure 2. $\ln \theta$ vs. time, with regression fit.

The constant Z is the slope of the regression line from the Figure 2 plots for each subject. From Equation (3), the constant depends only on k and the Size Factor. Size Factor is known; consequently, k is the slope of the linear fit for Z vs. Size Factor. Figure 3 shows the Z vs. Size Factor plot for all the UVa data as well as for Marshall and Hoare's data. The constant k for UVa data was found to be 0.51 with a R^2 value of 0.71. The constant k was 0.62 for Marshall and Hoare's data. This difference stems from the fact that Marshall and Hoare's subjects were allowed to cool uncovered, while UVa's were warmed in a shroud. Thus, the effective emissivity (ϵ) for the UVa experiment is lower, rendering k lower.

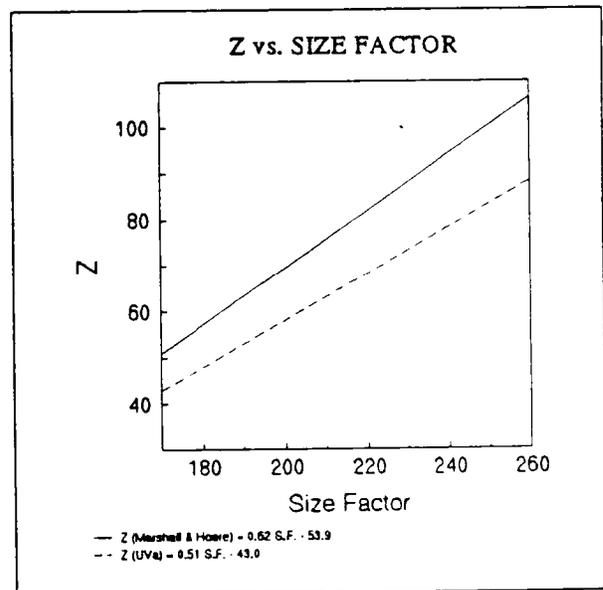


Figure 3. Z vs. Size Factor

Table 1 presents all the subject data used in the determination of k . The theoretical Z values for the 5th, 50th, and 95th percentile dummies are also computed using the k found from the regression.

Subject Data

Subject #	Height (cm.)	Weight (kg.)	Area (cm)	Size F.	Z calc.	Z meas.
15A	149.4	78.02	17257	177	47.2	63.5
15B	149.4	78.02	17257	177	47.2	40.3
16	155.7	62.60	16193	207	62.6	50.9
21	179.4	102.51	22129	173	45.2	30.2
26	175.4	64.87	17923	221	69.7	81.8
32	169.0	61.24	17024	222	70.2	61.0
36	183.2	59.88	17879	239	78.9	70.0
37	175.7	71.67	18722	209	63.6	79.0
39	176.8	50.35	16186	257	88.1	73.4
5th%	157.0	49.98	14804	237	77.8	76.7
50th%	175.0	78.15	19367	198	58.1	57.0
95th%	191.0	101.31	23042	182	49.8	48.9

Table 1. Subject Data and Z values.

Conclusions

The time to warm to ambient temperature for a supine cadaver, in a shroud ('body bag'), removed from refrigeration can now be found by the following method.

1. Measure subject height and mass.
2. Determine subject's surface area from Equation (2).
3. Compute the Size Factor. $S.F. = 0.8 A/m$.
4. Find Z from the Figure 3 regression fit.
 $Z = 0.51 S.F. - 43$
5. Choose the percent warming desired.
6. Use Equation (6) to find to find the time to warm, in hours.

$$t(\text{hrs.}) = \frac{\ln(\% \text{ warming})}{-Z \cdot 10^{-3}} \quad (6)$$

Equation (6) is shown graphically in Figure 4 for 95% and 99% warming. The theoretical times for 5th, 50th, and 95th percentile subjects are also shown. The total error in predicted warming time for the 95% warming curve is ± 5 hours.

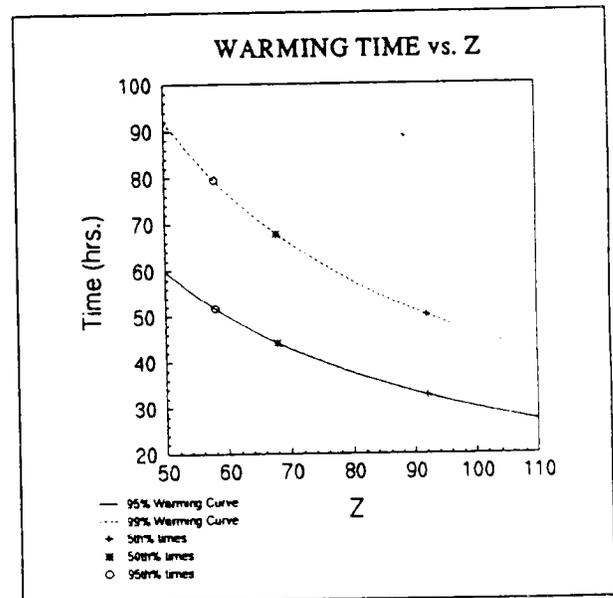


Figure 4. Warming time vs. Z.

Data in published literature have shown the properties of the body's soft tissues to vary considerably between refrigerated and ambient room temperatures. These property differences can cause changes in the dynamic response of human cadavers used as surrogates in impact tests. The complexity

of cadaver testing requires that as many variables as possible be controlled; consequently, body temperature should be standardized to 20-23 °C, ambient room temperature. The time needed for warming can now be predicted, given the subject's anthropometry. Thus, subjects can be removed in sufficient time to allow for thorough warming, while not being subjected to the unnecessary decay associated with prolonged warming periods and elevated temperatures.

References

- Ashman, R.B., Donofrio, M., et al.: Postmortem changes in the elastic properties of bone, *Proc. 28th Annu. Orthop. Res. Soc.*: New Orleans, 63, 1982.
- Bonfield, W., Tully, A.E.: Ultrasonic analysis of the Young's modulus of cortical bone, *J. Biomed. Eng.*, 4: 23-27, 1982.
- DuBois D., and DuBois, E. F.: A formula to estimate the approximate surface area if height and weight be known, *Arch. Int. Med.*, 17: 863-871, 1961.
- Duck, Francis A.: *Physical Properties of Tissue*, San Diego: Academic Press Inc., 1990, p. 141.
- Hardy, J. D., DuBois, E. F.: Technic of measuring radiation and convection, *J. Nutr.*, 15:477, 1938.
- Lam, T.C., Thomas, C. G., et al.: The effects of temperature on the viscoelastic properties of the rabbit medial collateral ligament, *J. Biomechanical Eng.*, 112: 147-152, 1990.
- Marshall, T. K.: Estimating the time of death, the use of the cooling formula in the study of postmortem body cooling, *J. Forensic Science*, 7: 189-211, 1962.
- Marshall, T. K., Hoare, F.E.: Estimating the time of death, the rectal cooling after death and its mathematical expression, *J. Forensic Science*, 7: 56-81, 1962.
- Viidik, A., Lewin, T.: Changes in tensile strength characteristics and histology of rabbit ligaments induced by different modes of postmortal storage, *Acta. Orthop. Scandinav.*, 37: 141-155, 1966.
- Warren, C. G., Lehmann, J. F., Koblanski, J. N.: Heat and stretch procedures: an evaluation using rat tail tendon, *Arch. Phys. Med & Rehab.*, 57: 122-126, 1976.
- Woo, S. L., Lee, T. Q., et al.: Temperature dependent behavior of the canine medial collateral ligament, *J. Biomechanical Eng.*, 109: 68-71, 1987.
- Yamada, H., Evans, F.G. (ed.), *Strength of Biological Materials*, Baltimore: The Williams and Wilkins Company, 1970.
- Yoon, H.S., Katz, J. L.: Temperature dependence of the ultrasonic velocities in bone, *IEEE Ultrasonics Symposium Proc.*: 395-398, 1976.

DISCUSSION

PAPER: **Warming of Cadaveric Specimens**

PRESENTER: Kelly B. Kennett, University of Virginia

Q: Guy Nusholtz, Chrysler Corporation

The warming issue is complicated by the fact that different parts of the body decay or degrade at different rates. Say you're looking to study the brain. If you allow the brain to sit out for, say 48-60 hours, then you may have compromised the experiment to the response of the brain in that. One of the things, I got a similar cooling curve to yours. And one of the things we decided, some fifteen years ago or so, was that about 30 hours, if you are doing, say a head impact study, was what you wanted to do. Otherwise the brain starts to fall apart. If you're doing bones, it really doesn't matter.

A: Right. That's what I was trying to say. The reason this data was taken from the thoracic core was that at the time it was taken we were doing thoracic injury response. Our main concern was, of course, the thorax. We have later data that we haven't had time to process and deal with the lower extremities now that we've done lower extremity research. In fact, it takes substantially less time for them to warm up, although the warming is just as important.

Q: Do you have any whole body impact data which indicates the magnitude of the issue in terms of impact response or injury potential?

A: No. We have not done a sled run, if that's what you mean. In particular, with a non-warmed-up body. Basically, we don't do enough runs to have the luxury to use one to test this particular question.

Q: Thank you. Very good presentation.

A: Thank you.

Q: David Porter, University of Louisville

I just have two quick questions. First one, most of your study of warming cadavers was actually thawing, right? You didn't actually warm above room temperature?

A: Well actually, sort of neither. No we didn't warm above room temperature, but when you say thawing, that implies to mean a phase change and we have tested frozen bodies, but that's entirely different analysis package and that's not included in what we've seen here. This data pertains basically to refrigerated to room temperature subjects.

Q: And refrigerated at zero degrees Celsius?

A: I think it is 2 degrees Celsius. More or less, just before the phase change.

Q: And I had another question about your last conclusion, that temperature change would cause

a variation in injury pattern.

A: Right.

Q: Do you have data on that?

A: What we've observed. We're just beginning what I told you about the pendulum test on isolated lower extremities. We're just now getting started with that. But what we have observed is that this condition of inherent plantar flexion from storage, if it's not taken care of, we get injuries to the Achilles tendon and the other joint structure at substantially less dorsiflexion than we do if we warm up the ankle and we exercise it, as we had before, so we can assume that the injury patterns do vary. But I don't have any specific numbers to tell you that 30 percent more injuries are this. I don't have that right now.

Q: One last question. In most of your studies you're talking about the leg presumably or the foot and ankle and yet you're measuring core body temperature and so you suggested that 30 hours is needed to thaw the body. Do you think that's really necessary for just testing of the leg?

A: No. In fact, when I answered Guy Nusholtz's question, I was saying that the lower extremities do, in fact, take less time to warm. The data that we have for the full body test was taken, like I said, when we were doing thoracic research and we still use this prediction method when we do our full sled test now. We're studying the question of lower extremities and, in fact, it takes less time to warm, but we want to make sure that these joints are, in fact, hopefully at room temperature.

Q: Thank you very much.

Q: Claude Tarriere, Renault Research, France

What do you think is the temperature of the cadaver? Are they at room temperature, probably I presume at 12, 10, 12 degrees maybe. So for the ligament elongation, you said there is a decrease of 10 percent maybe between 4 degrees and 20 degrees, so it is intermediate compared to the temperature. For instance, at 12 degrees, what could be the modification of ligament elongation. Do you know that?

A: The modification of elongation, you are saying, if you stopped your warming at 12 degrees instead of a full 20 degree range? Is that how I understand your question?

Q: Yes. Normal cadavers that we use are probably close to 10-20 degrees.

A: OK.

Q: OK, so could you say what could be the modification of ligament elongation at this temperature comparing to normal temperature for a human?

A: Right. We can only assume that hopefully that relationship is more or less linear and, in fact, sure if you have a body at room temperature, it's not going to respond the same as it would at

metabolic temperature. However, metabolic temperature is going to be hard to get just from a strictly realistic standpoint in the lab. It's going to be hard to warm the body up. It's going to be hard to keep it warm while you are positioning it and getting ready for your test. Really, right now the best we can do is to have them at warm temperature.

We are, in fact, looking at warming some of the bodies up to metabolic temperature. We do find, however, that at the same time, decomposition is increasing at an exponential rate and to warm the body up to metabolic temperature, you run into some real issues concerning decomposition of the tissue. Hopefully, what you want to do is maximize your biofidelic response in terms of temperature and in terms of tissue decomposition.

Q: Thank you.

Q: Barry Myers, Duke University

Regarding your last comment that there is a difference in soft tissue properties between room temperature and, say, 37 degrees Celsius, there is a lot of good data collected 10 years ago that says that, in fact, is not the case, that 20 degrees for structures like ligament and tendon is just fine.

A: OK.

Q: It's probably very worthwhile to go back, given the analysis that you presented, to say what is the variation in ligament properties between 4 degrees Celsius and 20 degrees Celsius because I would think it wouldn't be linear.

A: Right. In fact, it may not be. That's the question we are just beginning to look into. Basically, like I said, most of this data has not been taken with regard to the lower extremities where we're more concerned with the ligament response, but it was taken with regard to thoracic and viscous injury that we were looking at before.

Q: Frank Pintar, Medical College of Wisconsin

You guys have presented some stuff in the past on using the Winckler fluid for some of your cadaver specimens.

[Editor's note: See Crandall and Sturgill in the Proceedings for the 19th Workshop at San Diego, California in November 1991.]

A: Right.

Q: Could you use that for assisting in the warming process if you inject with a warmer fluid?

A: It's possible. We do, in fact, now use as our standard, the Winckler fluid, in all of our cadaver specimens. We have not, as of now, injected a warmer fluid but I suppose that we could. One thing that we have tried is to see if we could tailor the stiffness of a particular portion of the body to biofidelic response. So we've over-embalmed, let's say, some particular part of the body and then injected fluid right before testing, but it honestly didn't occur to us to inject warm fluid. Maybe we'll certainly take that into account.

Q: That might reduce the decomposition factor if it could warm it up faster.

A: Right. Maybe an idea to proceed from that would also be, you might want to inject some of this fluid into the extremities while you are waiting on the core to warm up to keep the extremities from decomposing.