

2002 MAFMA Final Report

Project Title: Magnetic Resonance Sensor for Grading of Canning Tomatoes Prior to Processing

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Objective Summary:

This project evaluated the use of a low field Proton Magnetic Resonance (^1H -MR) sensor for determining the maturity and processing characteristics of canning tomatoes. Specific objectives were:

1. To determine the effect of tomato maturity on the magnetic resonance (MR) spin-spin (T_2) relaxation curve for tomatoes at various stages of maturity.
2. To relate the observed differences in the parameters of the spin-spin relaxation curves to differences in tomato firmness, maturity, and processing characteristics.
3. To develop a procedure for determining the maturity and firmness of individual tomatoes using a low field ^1H -MR sensor.

Objective Accomplishments:

Objective 1: Effect of tomato maturity on the T_2 relaxation curve

Tomatoes used for these tests were grown in plots on a Purdue Farm approximately 8 miles from campus. The farm is used primarily by the Horticulture Department. Tomatoes were harvested and tested during both the 2003 and 2004 growing season. A no-cost extension of the project allowed data to be collected during the second growing season. This benefited the project because the experience gained during the 2003 growing season led to improvements to the procedures during the second growing season. Information on the varieties grown is included in Appendix A.

The tomatoes were harvested over a wide range of maturities. Fruit were taken to the laboratory where they were washed and hand sorted into the following six categories on the basis of visual perception of their color: green, breaker, turning, pink, light-red and red (USDA, 1997). In 2004, the color of each tomato was measured using a Hunter colorimeter. Readings were taken at four predetermined locations on each fruit, a^* (redness) and b^* (yellowness) were determined at each location, and the average value of a^*/b^* was calculated for each fruit. Other investigators have used this ratio to quantify color changes in tomatoes (Batu, 2004).

Individual tomatoes were placed in a low-field magnetic resonance sensor having a magnetic field strength of 0.1256 Tesla and a resonance frequency of approximately 5.35 MHz. Spin-spin (T_2) measurements were made using the Carr-Purcell-Meiboom-Gill (CPMG) pulse sequence

(Meiboom and Gill, 1958). The T_2 measurements were used because they are relatively insensitive to inhomogeneous magnetic fields and the magnet used was, by magnetic resonance standards, relatively inhomogeneous. The CPMG pulse sequence produces a series of echo peaks and the amplitudes of those peaks form an exponentially decaying curve. Each T_2 decay curve was normalized by dividing each echo peak amplitude by the amplitude of the curve's initial (maximum) peak. This eliminated differences in the signal caused by factors such as variations in the size of the tomatoes. The normalized data were fit to the following equation, consisting of two exponential terms: $A(t) = a_1 \exp(-t / T_2^a) + b_1 \exp(-t / T_2^b)$ where $A(t)$ is the amplitude of the echo peak at time "t." Because the curves were normalized, $A(0)$, the value of the amplitude for $t = 0$, was always equal to 1. The constants T_2^b and T_2^a were assumed to be the T_2 relaxation time constants (milliseconds) for free water in the tomatoes (which could contain dissolved solids) and for water associated with and influenced by other molecules such as carbohydrates, sugars, or cellulose. This interpretation is similar to the interpretation proposed by Snaar and Van As (1992) for their three-term exponential model of the T_2 relaxation signal of apple tissue. If the assumption is valid, then the coefficients a_1 and b_1 correspond to the fractions of partially bound water and free water in the tomatoes.

Figure 1 shows the cross sections of tomatoes at three stages of maturity – green, pink, and red. Saltveit (1991) reported that, during the early stages of ripening, the locular tissue of tomatoes rapidly changes from being very firm, similar to the pericarp wall, to an amorphous gel. Much of this change takes place during four stages of mature green (MG). In stage MG1 the locular tissue is green and firm. If the tomato is cut with a sharp knife during this stage, the seeds will also be cut through. At MG2 the seeds are displaced rather than cut when the sharp knife is applied. In MG3 the locule begins to gel but there is no red color inside the cut fruit. Finally, at MG4 nearly all of the locular tissue has gelled and there is a red coloration in some of the internal tissue. Most of the tomatoes tested in this study were MG3 or riper. Cross sections of tomatoes in the MG4, pink, and red stages are shown in Figure 1.



Figure 1: Cross sections of tomatoes classified as green (MG4), pink, and red.

The results of tests on whole tomatoes at various stages of ripeness are summarized in Table 1. The average a^*/b^* ratio of the tomatoes in each group was calculated from the Hunter Colorimeter measurements of a^* and b^* . Average values of the parameters in the T_2 relaxation model for each group (T_2^a , and T_2^b , the ratio of a_1 to b_1) are also included. The changes in a^*/b^* ratios indicate that the red color increased during ripening. The ratios for the green and breaker stages were negative and those of light-red and red tomatoes were above 0.7. The ratio increased more or less linearly as the tomatoes went from green to red. Analysis of variance (ANOVA) was used to compare the differences among the parameters listed in Table 1. Differences in a^*/b^* and T_2^b were highly significant ($P < 0.001$), while the differences in T_2^a were significant ($P < 0.05$). The T_2^b

Table 1. Comparison of color and the parameters of the T_2 relaxation curve model for whole tomatoes at various ripeness stages. Ten fruit from each ripeness category were tested. Values of the standard deviation of each measurement are given in parentheses.

Ripeness	Color (a*/b*)	a1/b1	T_2^a (ms)	T_2^b (ms)
Green	-0.26 (0.03)	0.068 (0.012)	29.2 (13.6)	1307.6 (53.9)
Breaker	-0.07 (0.07)	0.066 (0.011)	23.5 (9.4)	1368.5 (61.1)
Turning	0.10 (0.13)	0.065 (0.011)	20.7 (6.5)	1394.0 (43.5)
Pink	0.44 (0.15)	0.061 (0.009)	16.3 (6.8)	1451.7 (45.5)
Light-red	0.87 (0.09)	0.055 (0.006)	15.9 (4.4)	1486.7 (59.0)
Red	1.28 (0.02)	0.068 (0.016)	26.7 (14.0)	1308.7 (78.3)
P-value	< 0.001	0.081	0.018	< 0.001

values of green and red tomatoes had the fastest relaxation rates (the T_2^b values were the shortest) while the light red tomatoes, with a color between these two extremes, had the slowest relaxation time. The pattern for T_2^a was the opposite of the pattern for T_2^b . However, the standard deviations of the T_2^a values were much greater than those for the T_2^b values. Although the ratio a1/b1 followed the same pattern as T_2^a , the differences in a1/b1 among ripeness categories were not statistically significant.

A possible explanation of the trends in Table 1 relates to the state of water in the tomatoes. If it is assumed that the longer of the two relaxation times, T_2^b , is related to “free” water and the shorter relaxation time, T_2^a , is related to the partially bound water, then the coefficients a1 and b1 indicate the relative proportion of each in the tomato (Hills and Remigereau, 1997). Assuming this is correct, the observation that differences in a1/b1 are not statistically significant suggests that the proportion of partially bound and free water remains constant during ripening. The T_2^a value first decreased as ripeness category went from green to light red and then unexpectedly increased for the ripeness category of red. This suggests that the partially bound water becomes more tightly bound as the color changes from green to light red and then, as the deep red color develops, a change occurs that reduces the degree of binding. The T_2^b values show the opposite trend. They increase as the tomato goes from green to light-red and then decrease as the deep red color develops. This trend could be attributed to changes in the dissolved solids levels in the “free” water in the cells. This free water is probably in the cell vacuoles.

Saltveit (1991) observed that, as the fruit ripened from MG1 to MG3, there was an increase in intensity of the locular regions in the image of the cross section. This was attributed to the liquefaction of the locular tissue. The green tomatoes tested in this study were at or close to maturity level MG3 because their locular contents had already begun to liquefy. Results of a study on the locular contents of the tomatoes used in this study are included later in this report. The T_1 values of immature green and red tomatoes were reported in a second Magnetic Resonance Imaging (MRI) study (Ishida et al. 1989). They reported that T_1 values of the outer wall of the pericarp increased from 1.39 for the immature green tomato to 1.56 sec for the red tomato. The T_1 of the dissepiments separating the locules decreased from 1.48 for the green tomato to 0.98 for the red tomato and the T_1 of the columella in the center of the fruit decreased from 0.93 to 0.64. The placental tissue adjacent to the locules, to which the seeds were attached, gave no signal in the immature green tomato. In the tomato cross section images published by Saltveit (1991) the signal from the locular tissue was very weak for maturity MG1. Ishida and coworkers reported that the

locules in the red tomato had an average T_1 of 0.57, similar to the T_1 of the columella. Even though the green tomato tested in this study was mature, the T_2^a and T_2^b values follow trends similar to those reported by Ishida and coworkers. The ratio of their T_1 values (red to green) for the outer walls of the pericarp was 1.12. In this study, the ratio of the average T_2^b values of the light red versus the green tomatoes (Table 1) was 1.14. Similarly the ratios (green to red) of the T_1 values of the dissepiment and columella in Ishida's study were 0.66 and 0.69, respectively. The ratio of the average T_2^a values (light red to green) shown in Table 1 is 0.54. If the T_1 values of the columella and dissepiments of a MG3 tomato would be similar to the T_1 values of an immature green tomato (MG1), and if the T_2 and T_1 values of the tissues are similar, then the trends in this study are very similar to the trends in Ishida's study.

Changes in composition and in the amount of water in the tissue could explain the changes in T_2^a and T_2^b values. Ishida et al. noted that there was more water in the pericarp, placenta, and columella of the red tomato than in these same regions of the green tomato. The increase in water would explain the increase in T_2^b observed in this study. They attributed the decrease in the T_1 of the dissepiment and columella to the accumulation of stored materials, such as starches and proteins, in the tissue. This would also explain the decrease in T_2^a observed in these tests. As noted earlier, the "free: water in the tomatoes is probably located in the cell vacuoles and it probably contains solutes. In general, the T_2 values of aqueous solutions decrease as the concentration of solutes increases. Therefore, an increase in the solute concentration could be responsible for the decrease in T_2^b . The change in T_2^a and T_2^b of mature red versus over-mature (dark red) tomatoes may have been the result of changes in pectins or other compounds associated with softening of the fruit (Maclachlan and Brady, 1994)

As noted above, the locular region of the tomato liquefies as the tomato matures. Changes in the status of the water in the locular regions of mature tomatoes were investigated by conducting spin-spin relaxation tests on the contents of the locules that were removed from each of the whole tomatoes. The results are shown in Table 2. The average T_2^a of the locular tissue, 222 ms, is 10 times greater than the average T_2^a of the entire fruit, which is 22.1 ms. Apparently water in the locules is less tightly bound than the water that is bound in other portions of the tomato. The value of T_2^b of the locular tissue is only about 92 ms longer than the average T_2^b of the whole fruit. However, the differences in T_2^b among the various stages of maturity are statistically significant ($P < 0.05$) while the differences in T_2^a are not. The values of T_2^b fluctuated up and down as the maturity changed from green to light red. The T_2^b of the locular tissue from the red fruit, 1411 ms, was about 67 ms (~1%) shorter than the average T_2^b of all the fruits, which was 1492 ms and it was about 80 ms greater than the average T_2^b of all the green through light red fruits.

Another obvious difference between the locular tissue and the whole tomato was that the average $a1/b1$ ratio of the locular tissue was 3.5 times greater than the $a1/b1$ ratio of the whole tomatoes. This suggests that, even though the partially bound water in the locule is less tightly bound than it is in the rest of the fruit, a greater proportion of the locule water is partially bound. Cheng and Huber (1996) describe changes in cellular structure, and in pectin and alkali-soluble carbohydrates found in locular tissue as the fruit matures from immature green to mature green. They also reported less drastic changes in pectin and alkali-soluble carbohydrates between the mature green and breaker stages. The greatest change in T_2^b of the locule material occurs as the fruit matures from light red to dark red (Table 2). It seems likely that, just as the structure and composition of the locule change between immature green and mature green, there are changes in structure and composition between the light-red and red stages that cause the differences in T_2^b .

Table 2. Comparison of color and T2 parameters for whole tomatoes and the locule tissue from these tomatoes, which were at various stages of ripeness. Ten fruit from each category were tested. Values of the standard deviation of each measurement are given in parentheses.

Ripeness	Color (a*/b*)	Whole			Locule		
		a1/b1	T ₂ ^a	T ₂ ^b	a1/b1	T ₂ ^a	T ₂ ^b
Green	-0.26	0.068	29.2	1307.6	0.235	232.5	1505.8
	(0.03)	(0.012)	(13.6)	(53.9)	(0.030)	(25.5)	(54.3)
Breaker	-0.07	0.066	23.5	1368.5	0.212	214.8	1490.3
	(0.07)	(0.011)	(9.4)	(61.1)	(0.019)	(16.3)	(53.9)
Turning	0.10	0.065	20.7	1394.0	0.239	219.7	1450.7
	(0.13)	(0.011)	(6.5)	(43.5)	(0.042)	(13.7)	(57.0)
Pink	0.44	0.061	16.3	1451.7	0.212	211.4	1496.9
	(0.15)	(0.009)	(6.8)	(45.5)	(0.027)	(22.2)	(56.3)
Light-red	0.87	0.055	15.9	1486.7	0.219	221.2	1514.5
	(0.09)	(0.006)	(4.4)	(59.0)	(0.039)	(25.5)	(82.2)
Red	1.28	0.068	26.7	1308.7	0.235	231.3	1411.5
	(0.02)	(0.016)	(14.0)	(78.3)	(0.034)	(19.2)	(54.5)
Avg. - all	0.393	0.064	22.1	1386.2	0.225	221.8	1478.3
	(0.590)	(0.005)	(5.43)	(73.42)	(0.0124)	(8.56)	(39.4)
Avg. Green – Lt. Red	0.216	0.063	21.1	1401.7	0.200	219.9	1491.6
	(0.447)	(0.0051)	(5.51)	(70.25)	(0.0128)	(8.04)	(24.64)
P-value	< 0.001	0.081	0.018	< 0.001	0.232	0.155	0.003

Objective 2: Relating the magnetic resonance measurements to tomato firmness and quality.

Tomato firmness was evaluated by compressing individual tomatoes between two flat plates on an MTS/Sintech force-deformation testing machine using a compression speed of 5 mm/min. Two firmness indices were calculated for each test. The first was the deformation (in millimeters) produced by an applied load of 4.0 N. The second was the apparent modulus of elasticity, which was calculated from the deformation and the corresponding applied force using the Hertz contact equations (ASAE, 2001). A third measurement was used to determine the viscoelastic attributes of the tomatoes. Wu and Abbott (2002) developed this method, which is stress relaxation test, for the purpose of evaluating tomato firmness. In our experiments, the stress relaxation was measured at the same time as firmness by monitoring the force required to maintain the initial deformation attained when the 4.0 N load was applied. This force was recorded for 10 seconds after the crosshead on the MTS/Sintech machine was stopped as the tomato was held in a compressed position. The following three-parameter model for Y, the force required to maintain the deformation, was fit to the relaxation curves: $Y = 1 - A \ln(1 + t) - B t / (C + t)$ where t is relaxation time. Parameter A is related to the overall viscoelasticity of the sample with larger values indicating a less viscous tomato. Parameter B is related to the force required to maintain deformation after relaxation is nearly complete. When B increases, a smaller force is needed to maintain deformation. When parameter C increases, the relaxation rate also increases (Wu and Abbott, 2002). Wu and Abbot summarized the significance of these parameters as follows: “C, then, indicates quickness of relaxation; whereas A and B indicate extent of relaxation.”

There is sometimes a delay of several days between the harvesting and the processing of tomatoes. For this reason, an experiment was conducted to determine the effects of storage at room temperature on both the firmness and the T₂ relaxation parameters of tomatoes. Red tomatoes (a*/b* ratio of 1.28) were stored in the laboratory at room temperature (24°C ± 1°C) for 4, 8, and 13 days. Loss of water from the tomatoes was prevented by placing them in polyethylene bags that were tied shut. De-ionized water was sprayed on the tomatoes each day. In order to allow exchange of gases, the bags were perforated by puncturing them approximately 20 times with a screwdriver. This created holes in the bag approximately 5 mm in diameter. For each storage time, 10 tomatoes were tested.

The average values of the firmness measurements and the parameters in the stress relaxation model were determined for the tomatoes in each of ripeness category. In addition, the same measurements were taken on red tomatoes stored for 4, 8 and 13 days. The results are shown in Table 3. A Student-Newman-Keuls multiple range test (P = 0.05) was used to determine which means were significantly different. As the tomatoes matured, the deformation for an applied force of 4.0 N increased while the elastic modulus decreased. Similarly, as time of storage increased, the deformation caused by a 4.0 N load increased and their modulus of elasticity decreased.

Table 3. Summary of firmness measurements¹ on tomatoes at various stages of ripeness along with the changes in firmness parameters¹ of red tomatoes stored at room temperature. Ten fruit from each category were tested. Standard deviations are shown in parentheses.

Ripeness	Deformation, mm	EM, MPa	A	B	C
Green	0.36 ^a (0.06)	6.94 ^a (1.66)	0.041 ^a (0.004)	0.093 ^{a, b} (0.012)	0.505 ^a (0.092)
Breaker	0.42 ^a (0.08)	5.97 ^{a, b} (1.31)	0.044 ^{a, b} (0.002)	0.086 ^a (0.015)	0.487 ^{a, b} (0.062)
Turning	0.48 ^{a, b} (0.13)	5.21 ^b (2.61)	0.046 ^{b, c} (0.004)	0.095 ^{a, b, c} (0.010)	0.506 ^a (0.079)
Pink	0.59 ^{b, c} (0.08)	3.39 ^c (0.73)	0.049 ^{c, d} (0.004)	0.098 ^{a, b, c} (0.013)	0.466 ^{a, b, c} (0.045)
Light-red	0.71 ^{c, d} (0.15)	2.81 ^{c, d} (0.91)	0.050 ^{c, d} (0.005)	0.105 ^{b, c} (0.014)	0.457 ^{a, b, c} (0.078)
Red	0.82 ^{d, e} (0.14)	2.10 ^{c, d} (0.56)	0.050 ^{c, d} (0.003)	0.110 ^c (0.011)	0.403 ^{b, c} (0.033)
4d	0.84 ^{d, e} (0.11)	2.00 ^{c, d} (0.41)	0.052 ^d (0.001)	0.110 ^c (0.009)	0.387 ^c (0.047)
8d	0.87 ^e (0.22)	1.82 ^d (0.55)	0.053 ^d (0.007)	0.107 ^{b, c} (0.013)	0.404 ^{b, c} (0.052)
13d	0.90 ^e (0.23)	1.72 ^d (0.56)	0.054 ^d (0.002)	0.105 ^{b, c} (0.015)	0.427 ^{a, b, c} (0.075)
P-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

¹Means followed by different letters are significantly different (Student-Newman-Keuls multiple range test; P = 0.05)

Furthermore, the differences among the elastic moduli were statistically significant ($P < 0.001$). The changes are consistent with the expected softening (decrease in firmness) of tomatoes during ripening and subsequent storage.

The results of the stress relaxation tests are more difficult to interpret. Parameter A tended to increase slightly as the tomatoes ripened. However, it was relatively constant with time in storage. This indicates that the tomatoes became less viscous. In other words, they showed less resistance to deformation and the stresses relaxed as they ripened and that storage for up to 13 days had relatively little effect on their viscosity. The stress relaxes more rapidly in a less viscous tomato. One explanation of the change in parameter A is that the water in the fruit can be more easily re-distributed in the more mature fruit and that cells and clusters of cells can be more easily deformed because of chemical changes in the cell walls and connections between cells. Time in storage could have similar effects

Changes in the B and C parameters of the stress relaxation model shown in Table 3 are less obvious. Parameter B first decreases slightly and then increases as the fruit ripens. However, there is a small yet consistent decrease in B as time in storage increases. This decrease indicates that the force required to maintain the deformation decreases as time in storage increases. The change in B is consistent with the observation that fruit are “softer” and can be held in a squeezed configuration more easily when they have been stored for several days. The values of parameter C seem to decrease slightly as the tomato ripens, indicating that the stresses applied to riper tomatoes relax more quickly. On the other hand, there was no consistent trend related to the time in storage. One possible explanation of the faster relaxation of riper fruit is that the microstructure of the tissue can change more rapidly as a result of chemical changes in the cell constituents.

Results of color and T_2 measurements on stored tomatoes are summarized in Table 4. The fact that a^*/b^* ratios were almost identical indicates that the color did not change appreciably with time in storage. However, there were changes in the T_2 parameters with time in storage. The values of a_1/b_1 were greater for the tomatoes stored for 4 or more days. T_2^a increased after 4 days of storage and the average value of T_2^a was greater for 12 days of storage than for either 8 or 4 days of storage. The trend for the T_2^b values was the opposite of the trend for the T_2^a values. The average value of T_2^b decreased after 4 days of storage and the average T_2^b after 12 days of storage was less than the average value of T_2^b for either 4 or 8 days of storage. Possible explanations are the same as those presented in the discussion of Table 1. The change in T_2^a indicates that the partially bound water is held less tightly as time in storage increases. As noted before, T_2^b is affected by solids dissolved in the water that is in cell vacuoles. Therefore, these changes can be explained by shifts in composition and water content that occur during ripening and storage.

Table 4 includes the results of T_2 relaxation measurements on locule tissue that was removed from the stored tomatoes and tested separately. There were no discernable trends in a_1/b_1 , T_2^a , and T_2^b with time of storage and the differences were not statistically significant. The average values of a_1/b_1 , T_2^a and T_2^b of the locular tissue were similar to the respective values reported in Table 2 for whole red tomatoes. Apparently the state of the water in the locular material does not change appreciably with time of storage at room temperature for a storage period of up to 13 days.

Damage during harvesting and handling can also affect the processing quality of tomatoes. It seems likely that some of the cells in bruised tissue have been ruptured, causing a redistribution of the water. The effects of damage were determined on tomatoes obtained from the Red Gold Tomato processing facility in Elwood, Indiana on October 7, 2004. Tomatoes were arriving on

Table 4. Comparison of color¹ and the parameters¹ of the T₂ relaxation curve model for whole red tomatoes stored for up to 13 days. Ten fruit from each category were tested. The standard deviation of each measurement is given in parentheses.

Storage Time	Color (a*/b*)	Whole			Locule		
		a1/b1	T ₂ ^a	T ₂ ^b	a1/b1	T ₂ ^a	T ₂ ^b
Nn	1.28 (0.02)	0.068 ^a (0.016)	26.7 ^a (14.0)	1308.7 ^a (78.3)	0.235 ^a (0.034)	231.3 ^b (19.2)	1411.5 ^a (54.5)
4d	1.28 (0.03)	0.111 ^c (0.012)	76.9 ^b (12.4)	1181.0 ^b (70.9)	0.223 ^a (0.025)	247.5 ^b (23.4)	1424.3 ^a (55.2)
8d	1.29 (0.06)	0.084 ^b (0.016)	69.8 ^b (32.1)	1217.1 ^b (81.0)	0.200 ^a (0.059)	201.9 ^a (50.8)	1366.8 ^a (71.0)
13d	1.28 (0.04)	0.094 ^b (0.016)	94.7 ^b (28.4)	1155.2 ^b (72.0)	0.218 ^a (0.024)	259.8 ^b (38.1)	1408.5 ^a (102.9)
Average	1.28	0.089 (0.022)	67.0 (33.8)	1215.5 (98.2)	0.219 (0.039)	235.1 (40.3)	1402.8 (74.0)
P-value	0.994	< 0.001	< 0.001	0.001	0.236	0.005	0.342

¹Means followed by different letters are significantly different (Student-Newman-Keuls multiple range test; P =0.05)

trucks, which were being unloaded using a stream of water to wash them from the truck into a small reservoir where they would float on or near the surface of the water. The tomatoes to be tested were collected from the conveyor that lifted tomatoes from the reservoir and transported them to the sorting and processing areas of the plant. It should be noted that many of the tomatoes had been bruised by mechanical harvesting and subsequent handling. The tomatoes were brought back to Lafayette and stored in a walk-in cooler at approximately 3°C until they could be tested. They were sorted into three categories – those with no bruises, those with slight bruising, and those with severe bruising.

The T₂ relaxation model parameters for each group of tomatoes collected from the processing facility are shown in Table 5. The differences in T₂^a and a1/b1 among the groups of tomatoes with no damage, slight damage and severe damage were statistically significant (P<0.001). Although the values of T₂^b are greater for the bruised tomatoes, severity of bruising did not appear to affect T₂^b and the differences among the three categories were not statistically significant. However, the values of both T₂^a and a1/b1 did vary with severity of damage. The average value of T₂^b of the damaged tomatoes (Table 5) was almost the same as the average T₂^b for red tomatoes shown in Table 1. The average T₂^b of the healthy tomatoes obtained from the processors was about 90 ms shorter. The difference in the average T₂^b values may be related to variety or the effects of mechanical harvesting and handling. In addition, the a1/b1 ratio of the tomatoes with no visible damage was about 1.8 times the ratio for red tomatoes as shown in Table 1 and the average T₂^a of the tomatoes with no visible damage was about 1.5 times the T₂^a for the red tomatoes in Table 1. This observation, combined with the fact that both T₂^a and the a1/b1 ratio increase as a result of damage (Table 5), suggest that there may have been “invisible” damage during harvesting and handling that increased T₂^a and a1/b1 of the tomatoes with no visible damage.

Table 5. Parameters¹ of the T₂ relaxation curve model for tomatoes without damage and for tomatoes with slight or severe bruising. Their standard deviations are given in parentheses.

Degree	T ₂ ^a (ms)	T ₂ ^b (ms)	a1/b1
None	53.8 ^a (38.4)	1216.3 ^a (63.4)	0.122 ^a (0.078)
Slight	101.8 ^b (19.1)	1360.3 ^a (153.4)	0.189 ^a (0.065)
Severe	121.3 ^c (29.1)	1284.6 ^a (109.0)	0.298 ^b (0.1)
P-value	< 0.001	0.068	0.001

¹Means followed by different letters are significantly different (Student-Newman-Keuls multiple range test; P = 0.05)

Relationships among the color, firmness, viscoelastic, and magnetic resonance measurements made on the tomatoes at various stages of ripeness were investigated using linear regression techniques. The results are summarized in Table 6. The highest correlations obtained were between color and the two measures of firmness, deformation (0.68) and elastic modulus ($r^2 = 0.70$). The color was also correlated (0.49) with the parameter A from the stress relaxation model. The remaining correlations are relatively low. Deformation was best correlated with the magnetic resonance parameter(s) $1/T_2^b$ ($r^2 = 0.31$), $T_2^a + T_2^b$ ($r^2 = 0.30$), and $T_2^b - T_2^a$ ($r^2 = 0.33$). The elastic modulus was also relatively well correlated with these same parameters ($r^2 \cong 0.3$). The magnetic resonance parameter $1/T_2^b$ was best correlated with viscoelastic properties ($r^2 = 0.26$ for both A and B).

Table 6. Correlation coefficients (r) for linear regression among color, firmness, viscoelastic, and magnetic resonance parameters of the tomatoes stages of maturity ranging from green and light red.

Parameter	Def., mm	EM, MPa	A	B	C
Color	0.801	-0.717	0.644	0.441	-0.266
a1/b1	-0.320	0.171	-0.305	-0.225	0.242
T ₂ ^a	-0.336	0.241	-0.364	-0.239	0.153
T ₂ ^b	0.565	-0.552	0.521	0.508	-0.089
1/T ₂ ^a	0.398	-0.322	0.272	0.222	-0.207
1/T ₂ ^b	-0.554	0.545	-0.512	-0.507	0.078
T ₂ ^a /T ₂ ^b	-0.367	0.279	-0.399	-0.288	0.137
T ₂ ^b /T ₂ ^a	0.460	-0.385	0.330	0.278	-0.219
T ₂ ^a + T ₂ ^b	0.550	-0.548	0.500	0.503	-0.075
T ₂ ^b - T ₂ ^a	0.572	-0.549	0.533	0.507	-0.102
1/T ₂ ^a + 1/T ₂ ^b	0.397	-0.322	0.272	0.222	-0.207
1 / (T ₂ ^a + T ₂ ^b)	-0.542	0.544	-0.491	-0.501	0.066

Table 7. Linear regression and linear multiple regression analysis of firmness measurements versus parameters from the model of the spin-spin relaxation (T_2) curves of whole tomatoes in the maturity categories green to light red. Outliers were deleted before the models were developed.

Model	n	R ²	SEE	P-values
$D = - 2.76 + 0.0857 T_2^a + 0.00238 T_2^b - 0.000064 T_2^a T_2^b$	49	0.466	0.114	< 0.0001
$D = - 1.06 + 0.00112 T_2^b$	49	0.373	0.120	< 0.0001
$EM = 5.49 - 367/ T_2^a + 497,341/(T_2^a T_2^b)$	49	0.399	1.541	
$EM = 24.7 - 0.0142 T_2^b$	49	0.362	1.571	< 0.0001
$A = 0.0442 + 0.773/ T_2^a - 1043/(T_2^a T_2^b)$	50	0.271	0.004	
$A = 0.0011 + 0.000032 T_2^b$	50	0.271	0.004	< 0.0001
$B = 0.216 - 168/T_2^b$	49	0.314	0.011	
$B = - 0.0257 + 0.000087 T_2^b$	49	0.311	0.011	< 0.0001
$C = 0.604 - 0.000085 T_2^b$	49	0.018	0.066	0.355

According to the results in Table 3, the firmness of tomatoes decreases as the tomatoes mature. At the same time, the average values of T_2^a for the maturity classes (Table 1) decrease while the values of T_2^b increase. This is an indication that both T_2^a and T_2^b are indicators of maturity and that multiple linear regression could be used to develop a prediction of firmness. , the relationship between firmness and the T_2 values was examined using multiple linear regression analysis. The linear and multiple linear regression models having the highest R² values are shown in Table 7. A total of 50 measurements (five maturity classes with 10 tomatoes per class) were examined. With the exception of the model for the “A” parameter in the model of the stress relaxation curve, one outlier was deleted before the models were developed. A point was considered an outlier if the residual divided by the square root of the mean square error exceeded a value of 3.0. The multiple linear regression models gave slightly better correlations when predicting deformation and elastic modulus. Considering the parameters in the stress relaxation model, the linear and multiple linear models had almost identical correlations for the parameter “A” while the linear regression gave a better model for “B” and the multiple linear regression model could not predict “C.”

The data in Table 6 indicate that color was the best predictor of firmness when firmness was measured on the basis of deformation for an applied force of 4 N ($r^2 = 0.68$) or the elastic modulus calculated for an applied force of 4 N ($r^2 = 0.70$). Although the correlations between these firmness measurements and the MR parameters were statistically significant, the coefficients of determination were rather low ($r^2 < 0.463$). Therefore, there are factors other than firmness that affect the spin-spin relaxation signal of the tomatoes. Based on the results in Table 5 and experience with other fruit (Cho et al. 1993; Keener et al. 1999; Jung et al., 1998) these other factors include bruising and other types of internal damage and soluble solids content.

The ultimate goal of this research was to determine whether a low field proton magnetic resonance sensor could be used for evaluating the quality of tomatoes that are to be processed into diced tomatoes. One of the major quality concerns for diced tomatoes is their firmness. Although it

seems likely that firmness prior to processing is an important quality parameter affecting the firmness of the diced tomatoes, other factors could also have an influence. The potential for quality sorting was evaluated by sorting tomatoes on the basis of both color and T_2^b value. Approximately 140 tomatoes (about 12kg), which produced approximately 24 cans of diced tomatoes, were sorted by each method. Color sorting involved visually evaluating the color and placing the tomatoes into categories of pink, light-red, and red. For magnetic resonance sensing, the T_2^b value of the tomatoes was determined and they were separated into the following groups: 1110 to 1200 ms (low), 1200 to 1350 ms (intermediate), and 1350 to 1410 ms (high).

After the tomatoes had been sorted, the intact tomatoes were prepared for peeling immersing them in boiling water for 1 minute and in ice water for 1 minute. The tomato skins were removed by peeling them from the tomato by hand with the aid of a knife. The peeled whole tomatoes were diced into approximately $1.9 \times 1.9 \times 1.9$ cm cubes using a pilot scale dicing machine. Immediately after dicing, approximately 1.5 kg of diced tomatoes was dipped in 4 liter container filled with calcium chloride solution (0.5 %, 35 °C) for 1 minute. The samples were drained and then placed in 24 No. 300 size cans (300×407 cm). The canned diced tomatoes were retorted in at 115 °C (240 °F) for 20 minutes and then cooled with water for 20 minutes. The samples were preserved in a laboratory at room temperature (24 °C) for several months before firmness measurements were conducted.

The firmness of the canned, diced tomatoes was determined using both the Kramer Shear cell and squeezing flow rheometry. In the shear tests, 100 g. of diced tomatoes were placed in the reservoir of the Kramer Shear cell and the shearing mechanism was pushed through the cell at a rate of 60 mm/min. One important modification to the test fixture was made for the 2004 tests (the second year of testing). A swivel connection was added between the shearing mechanism and the rod, which was in turn connected to the load cell using a drill chuck. This permitted slight movements of the fixture so that there was no binding between the “fingers” of the shearing mechanism and the slots in the cover for the load cell. After this modification was made, the results were more consistent.

Squeezing flow rheometry, the second technique used to determine firmness of the diced tomatoes, consisted of squeezing the diced tomatoes between two circular Teflon discs (Suwonsichon and Peleg, 1999). For these tests, the discs had diameters of 13.0 cm. Prior to testing the tomatoes, the procedure was evaluated by testing a standard with known viscosity, Dow Corning 200 (R) fluid. This fluid has a viscosity of 5405 Pa-sec. For tests with diced tomatoes, a 120 g sample was placed on the lower plate, which was resting in a pan between the uprights of the load frame and supported by the bottom of the load frame. The sample of diced tomatoes was spread evenly over the bottom plate and the upper plate was lowered into position until there was a gap of 8 mm separating the plates. When the test began, the upper plate was lowered at a rate of 15 mm/min until there was a gap of 2 mm remaining. The “viscosity” of the sample in kPa-sec a strain rate of 0.05 sec^{-1} was calculated using Matlab software (version 6.5, The Mathworks, Inc., Natick, MA). Upon completion of a test, the Teflon plates were cleaned by rinsing them with water and wiping them dry with a paper towel.

The elongational viscosity, μ as a function of the elongational strain rate, $\dot{\epsilon}^\circ$, was calculated using the following equations,

$$\dot{\epsilon}^\circ = V/(2H)$$

$$\mu = 2HF/(\pi R^2 V)$$

where V is the compression rate, H is the height of the specimen (the distance between the plates) at time “ t ”, F is force, and R is the plates radius (Campanella and Peleg, 2002).

Results of the firmness tests on the tomatoes sorted on the basis of color and of T_2^b are given in Table 8. Neither of the sorting techniques indicated clear differences in firmness among the canned diced tomatoes. The differences in squeezing flow viscosity of the samples sorted by color and the shear force of the samples sorted on the basis of T_2^b were significant at the relatively low 10% level of significance. All of the diced tomatoes were relatively firm. This may have been associated with the fact that they were all picked by hand and therefore the handling was relatively gentle. One difficulty encountered with the squeezing flow viscometer should be noted. The gap between the plates at the end of the test was so small that the sound of tomato seeds cracking could be heard. It seems likely that this influenced the results.

Table 8. Comparison of the rheological properties of diced tomatoes classified on the basis of color and on the basis of T_2^b .

				P-value
Samples sorted on the basis of Color:				
Category:	Pink	Light-red	Red	
Shear force, N	403.0 (17.4)	422.9 (36.1)	429.9 (22.6)	0.374
E. Viscosity, kPa·sec	1705.3 (53.4)	1498.0 (120.1)	1537.9 (167.7)	0.089
Samples sorted on the basis of T_2^b:				
Category	Slow	Intermediate	Fast	
Shear force, N	442.2 (60.0)	479.8 (34.9)	569.2 (97.1)	0.072
E. Viscosity, kPa·sec	1645.6 (236.8)	1625.6 (81.5)	1605.4 (127.8)	0.941

If the tests on diced tomatoes were repeated, several modifications should be made. First, it would be better to conduct tests on tomatoes obtained from a processor, providing they had a sufficient range in maturity. Second, all firmness tests should be conducted with the Kramer shear cell to prevent the interference caused by compression and cracking of tomato seeds. Third, it may be better to use a two-step process for the MR sorting of tomatoes. The first step would consist of removing the dark red tomatoes. It would be followed by classification of the tomatoes into categories on the basis of the values of T_2^b . For the purpose of assessing the ability of the MR sensor to sort for quality, the ranges in the T_2^b values for the three categories could be narrowed.

Objective 3: Develop a procedure for using a low field MR sensor for determining the maturity and firmness of individual tomatoes.

As noted above, the MR sensor did not give a clear indication of tomato firmness. These results are different from those reported by Kim et al. (1994) who used an imaging system to determine the average T_2 values of scanned cross sections of tomatoes. They found that T_2 values increased with ripeness and that $1/T_2$ was correlated with firmness ($r^2 = 0.847$). However, a more detailed examination of their data, included in Kim (1995), indicates that their tomatoes had a much greater variation in firmness (ratio of soft/firm $\cong 16$). For the hand harvested tomatoes used in this study, color sorting would have been more effective method of evaluating firmness.

It may still be possible to use an MR sensor for evaluating some aspects of processing quality. However, this would have to be confirmed by additional tests on machine harvested tomatoes. One factor that should be investigated is the effect of pre-sorting on the basis of color. The deep red, over-mature tomatoes could be removed and tested separately. This would be beneficial because the T_2^b of green tomatoes and dark red (over mature) tomatoes are nearly equal. Machine harvested tomatoes should be used because the results from this study indicate that the MR sensor can detect internal damage to the tomatoes and damage could greatly affect firmness and processing quality. All three of the MR parameters determined from the model of the T_2 decay curves, T_2^a , T_2^b and $a1/b1$, are affected by damage. Unfortunately, this was discovered when the project was nearly completed and there were no additional funds available to continue the tests. The values of T_2^a and T_2^b also change with time of storage. It seems likely that the processing quality of tomatoes will decrease with time of holding prior to processing. Therefore, the effects of holding the machine harvested tomatoes at ambient temperature for several days (5 to 7) prior to processing should also be evaluated.

Unexpected Findings:

Before we began this research, we anticipated that the magnetic resonance signals for green tomatoes would be different from those of ripe tomatoes and that there would be a gradual shift in the signals as the tomatoes ripened. Our tests indicated that the T_2 relaxation signal gradually changed as the tomatoes ripened. This change was reflected in the changes in the T_2^a and T_2^b parameters of the two-term exponential model with ripening. T_2^a gradually decreased and T_2^b gradually increased until the tomatoes reached the light-red stage of ripeness. What was not expected was that the trend for both T_2^a and T_2^b was suddenly reversed as the tomatoes went from light-red to red. This was true for tomatoes grown in both 2003 and 2004. It seems likely that this is related to a physiological change or to changes in the constituent compounds. Additional research is needed to explain the results.

Practical Impacts of this Research:

The U.S. is one of the world's leading producers of tomatoes. It ranks second only to China. According to the Economic Research Service, the annual farm value of tomatoes processed in the U.S. averaged \$710 million between 1997 and 1999. Increases in efficiency of processing can therefore result in significant savings. Tomatoes are also important in the Midwest, where processors focus on higher value canned products. The average annual farm value of tomatoes processed in Indiana, Michigan, and Ohio was \$55.5 million. The value of processed products would be several times greater. The yield of peeled tomatoes is typically 17 to 25% of the incoming weight, and its value is approximately 3 times greater than the value of stock diverted to other uses. Processors state that even a 1 or 2% increase in yield makes a great difference to them.

Results of this study suggest that it may be possible to use MR sensing to assess the level of internal damage to the tomatoes and the extent of changes caused by holding the tomatoes at ambient temperature for several days prior to processing. This should be confirmed by additional tests on machine harvested tomatoes. Given the current status of magnetic resonance technology, it seems impractical to test every tomato being processed. Several processors in Ohio and Indiana have developed methodology for sampling tomatoes as they arrive at their facilities. The processor could use the magnetic resonance sensor to evaluate the damage and deterioration of the tomatoes at the grading station. A better evaluation of damage would allow the processor to adjust the price

paid to the producer in accordance with the quality of the tomatoes. It would be an incentive for the grower to deliver higher quality tomatoes. Tomatoes with lower canning quality should be processed into sauce or the processor could adjust the peeling process to maximize the yield of diced tomatoes. This would increase the product yield and reduce the amount of waste produced.

It may also be possible to take the magnetic resonance sensor to the field where tomatoes are being harvested. A sample of harvested tomatoes could be tested with the sensor to provide the producer with a better idea of the tomato quality. This would provide an incentive for making adjustments to the harvester to reduce damage.

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Appendix A
Information on Red Gold Varieties Grown in Test Plots

Variety	Years Grown	Relative Days to Maturity	Color Uniformity	Firmness	Description
GEM 818	2004	108	Excellent	Good	A main season variety. The jointless fruit is ovate shaped and weighs approximately 2.5 oz. It also has excellent interior color. GEM 818 is an excellent yielder and has very good traits for the whole peel and diced pack markets. It has medium to large vines that provide good fruit cover to optimize fruit quality. This variety is known to have very consistent color with a high percentage of A quality fruit. This variety is resistant to Verticillium and Fusarium Wilt.
GEM 611	2003, 2004	103	Good	Excellent	an early season hybrid. It has medium to large jointless blocky fruit. It also has good holding ability with good color. The fruit weighs approximately 2.6 oz., and is excellent for whole peel and diced pack. The medium to large sized vines are capable of producing large yields on a consistent basis. This variety is resistant to Verticillium and Fusarium Wilt.
GEM 401	2004	112			This variety is not commercially available and is kept within the company. A late season hybrid. It has very good internal color and would have very good whole peel and diced recovery. However, the plant is on the lower end of field yield consistency.
GEM 331	2003	331			A main season hybrid. It has a medium to large vine type that lays on the bed well. The fruit is jointless and has an ovate shape. The fruit weighs approximately 2.5 oz. Gem 331 is best known for its ability to yield under adverse conditions. It is a very consistent variety over many soil types and production practices.
GEM 111	2003, 2004	112	Good	Excellent	A late maturing hybrid. The jointless fruit is blocky and weighs approximately 2.5 oz. This GEM variety shows good holding ability and is known to be an excellent yielder. The variety will set fruit under high stress condition such as drought or extreme heat. 111 has good color that works well in a peeled or diced product. The vines are medium sized and lay on the bed very well. This variety is very sound agronomically and will work well and many conditions. GEM 111 is resistant to Verticillium and Fusarium Wilt.

Additional Notes:

The information shown in the table was obtained from Mr. Jim Holloway, a Red Gold employee, in an electronic mail message dated July 15, 2005. The descriptions of GEM 111, 331, 611, and 818 were obtained from a Red Gold document entitled “GEM Vegetable Seed Tomato Variety Descriptions.”

In a follow-up electronic mail message, also sent on July 15, Jim was asked whether 611 was better suited for peeling and dicing than the other varieties, whether 818 had better color uniformity, and whether 818, 111 or 331 had any distinctive processing characteristics. In response, Jim provided the following additional comments in an electronic mail message dated July 19, 2005:

“GEM 611 is good for whole peel and diced tomato pack but not head and shoulders above any other variety listed. Since Red Gold is primarily looking for Whole Peel and Diced Tomatoes during our fresh pack all the varieties that we use are geared towards those uses. With 401 having the best color uniformity and going down in this order 818, 611, 331 and 111 being near the bottom. The better the color uniformity and the firmness the better that they are to whole peel and dice.”