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Cold-Hardiness Evaluation of Grapevine Buds and Cane Tissues

Lynn J. Mills,[1] John C. Ferguson,[2] and Markus Keller[3]*

Abstract: A system for differential thermal analysis (DTA) was constructed to assess cold hardiness of grapevine buds and cane tissues. This updated system incorporated a sample chamber of our own design with a commercially available programmable freezer and data acquisition system (DAS). Thermoelectric modules (TEM) were used to sense exotherms that are produced when water or tissues freeze. The TEM signals recorded by the DAS at 15 sec intervals were downloaded directly to an Excel spreadsheet. The DTA system was designed to test up to 35 samples of five buds or three canes per TEM simultaneously. Bud and cane low temperature exotherms (LTE) recorded by this system correlated very closely with those of a standard system, and the extent of cane phloem and xylem injury, based on tissue browning, corresponded well with expected injury based on LTE analysis. The LTEs of moist buds were 3°C to 4°C higher and those of moist canes 2°C higher than LTEs of corresponding dry tissues, indicating that surface moisture increases the susceptibility to cold injury. Cold hardiness of eight grape cultivars increased from late fall through mid-January, after which buds and canes began to deacclimate. Riesling was the hardiest of all cultivars tested. Chardonnay reached similar levels in midwinter, but was considerably less hardy in late fall and late winter. Pinot gris and Viognier were the least hardy among the white winegrape cultivars. Among red winegrape cultivars, Cabernet Sauvignon was generally the hardiest and Merlot the least hardy, with Malbec and Syrah being intermediate.

Key words: *Vitis vinifera*, cultivar, supercooling, exotherm, DTA analysis, bud, phloem, xylem

Freeze injury can dramatically reduce yield or even be a limiting factor to growing European winegrapes (*Vitis vinifera* L.) in northern latitudes, where critically low winter temperatures can occur. In addition, late spring and early fall frosts can occur in areas not normally affected by low midwinter temperatures (Fennell 2004, Johnson and Howell 1981). During active summer growth, grapevines are susceptible to freeze damage, but during the dormant season they have the ability to supercool, which allows bud, cane, and trunk tissues to become acclimated to temperatures well below -10°C (Andrews et al. 1984, Burke et al. 1976). However, lethally low temperatures fluctuate depending on preceding temperatures and photoperiod. Thus our laboratory routinely evaluates cold hardiness of *V. vinifera* and *Vitis labruscana* Bailey cultivars throughout the dormant season. Critical temperatures for bud, phloem, and xylem injury are regularly posted on the Internet (http://fruit.wsu.edu/Grapeweb/frigid.htm) so that growers may use the information for decisions regarding measures and timing of frost control (such as wind machines).

Techniques for evaluating lethal temperatures in various crops have evolved from making observations following naturally occurring low temperature events to evaluating injury under controlled environmental conditions (Burke et al. 1976). When supercooled water freezes extracellularly, the heat released is referred to as a high-temperature exotherm (HTE); extracellular freezing is considered nonlethal (Burke et al. 1976). On the other hand, the freezing of intracellular water creates a similar, low-temperature exotherm (LTE) and is lethal (Burke et al. 1976). Differential thermal analysis (DTA) was first used to detect LTEs in *Prunus* species by Quamme (1973). The relationship between LTE and cane and bud injury in grapevines was confirmed by Pierquet and Stushnoff (1980). Once the LTEs are identified for a population of buds, the LTE_{50} (temperature required to kill 50% of the buds) can be calculated (Proebsting et al. 1980). DTA is not only used to conduct research on the mechanisms of freeze tolerance, but also to predict the critical (lethal) temperatures for grapevines.

Various chamber designs for DTA analysis have been described (Andrews et al. 1983, 1984, Barney et al. 1994, Wolf and Pool 1986). The standard system used in our laboratory was described by Wample et al. (1990). Although still functional, it had been in use since 1986 with outdated XT computer technology, now increasingly more

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difficult to maintain. The computer controlled the cooling rate in the freezer by constantly switching the compressor on and off, which made it prone to malfunction. In addition, the data analysis and graphing programs based on DOS and BASIC were obsolete, time-consuming, and awkward. Thus the major objective was to update the computer-controlled freezing and data acquisition system for DTA analysis of dormant grape buds and cane tissues (phloem and xylem). The updated system needed to incorporate ease of temperature programming, reliable data acquisition, environmentally friendly freezer technology, and the ability to use readily available software for data analysis without sacrificing the ability to predict exothermic events accurately.

Under field conditions, the presence of surface moisture can influence the temperature at which buds and canes freeze. Dry buds have been reported to tolerate temperatures as much as 4°C lower than wet buds (Johnson and Howell 1981, Wolf and Pool 1987). Therefore, another objective of this study was to evaluate the influence of surface moisture on bud LTEs obtained using DTA analysis. The final objective was to compare the progression of cold hardiness during the dormant season of emerging cultivars in eastern Washington with that of commonly grown cultivars. The vineyard area planted to Syrah has increased exponentially over the last few years, while Malbec and Pinot gris are not widely planted but are cultivars of potential interest to viticulturists and winemakers. Since their ability to withstand cold winter temperatures is unknown, this study was undertaken to provide information that will reduce the risks involved in decisions on planting and site selection.

Materials and Methods

The updated DTA system incorporated the same thermoelectric modules (TEMs) (model CP1.4-127-045L; Melcor Corporation, Trenton, NJ) that had been used in the standard system (Wample et al. 1990). These sensitive Peltier plates detect temperature gradients generated by the exotherms and convert the thermal signals to voltage (mV) outputs. In addition, thermistors (model 44212; YSI, Dayton, OH) were used for chamber temperature measurements. The Keithley Multimeter Data Acquisition System (DAS) (model 2700-DAQ-40; Keithley Instruments, Cleveland, OH) was used to measure and collect voltage output. The DAS scans up to 40 channels of the TEMs and thermistors every 15 sec and runs in conjunction with the program ExcelLINX (Keithley Instruments), an add-in to Excel (Microsoft, Redmond, WA). The output in mV is placed directly in Excel, where the data are processed and graphed two-dimensionally (thermistor output on the x axis versus TEM output on the y axis).

A programmable freezer, the Tenney Environmental Test Chamber (model T2C, Thermal Product Solutions, Williamsport, PA), was linked with the DAS. The freezer was equipped with a temperature controller (Watlow Series 942, Watlow Electric Manufacturing, St. Louis, MO), which allowed up to 24 temperature steps per run over a range of -75°C to 200°C. This range affords great flexibility in programming different temperature profiles.

The cooling rate can have a significant effect on the temperature at which supercooled tissue freezes because of the mechanics of ice nucleation (Gusta et al. 2003). Although rates of temperature decline of 1.5 to 10°C/hr have produced consistent LTE temperatures (Fennell 2004), we wanted to be able to reproduce the same conditions as our standard system and those of other laboratories (Andrews el at. 1984, Barney et al. 1994, Quamme 1973, Wample et al. 1990, Wolf and Pool 1986). Furthermore, rapid cooling rates (for example, 10°C/hr) are not realistic in nature and not representative of natural freezing events. In preliminary tests the freezer accurately followed the programmed temperature profile with cooling and warming rates of 4°C/hr (data not shown).

Each sample chamber consisted of a tray and a lid (33 cm long x 23 cm wide x 7 cm high) constructed from 6-mm thick PVC sheeting. PVC-walled wells (4 cm x 4 cm x 15 mm deep) were made on each tray to snugly hold 10 TEMs per tray (Figure 1A). One thermistor was affixed to a TEM not connected to the DAS in a center well of each tray to monitor the freezer temperature. No samples were placed in the well with the thermistor, so that nine wells per tray could be loaded with bud or cane samples. Holes (14 mm diam) were drilled between wells of the tray, through the tray supports, and in the lid to facilitate air circulation (Figure 1A,B,C).

Cold-hardiness determination. Dormant buds from nodes four through eight (to preserve the more basal nodes for spur-pruning) were cut from canes of field-grown grapevines (see below for cultivar and vineyard details). Approximately 2 mm of intact cane tissue surrounding and underlying the bud was left to allow the bud to supercool (Andrews et al. 1984, Wolf and Pool 1987). Four to five buds were placed directly on each TEM with the cut surface facing up; the attached cane tissue prevented the buds from flipping over. Approximately 35-mm long cylindrical sections of cane were cut from the internode area between nodes four and eight, and two to three such cane pieces were placed directly on each TEM. Cane pieces were left intact, since previous experience indicated that longitudinal sectioning did not improve the TEM output (unpublished data). One TEM in the top tray was left empty as a control for signal noise that was common to all TEMs. Preliminary tests showed that one empty TEM was sufficient for all four trays and that one empty TEM per tray did not improve accuracy. Foam insulation pads (4 cm x 4 cm x 9 mm thick) were placed on top of buds or cane pieces in each well to ensure adequate contact between the tissues and TEM. The chamber lid was then tightened (Figure 1B) and the chambers placed in the freezer. Up to four chambers were stacked in the freezer (Figure 1D) for a maximum of 35 TEMs loaded per run (175 buds or 105 cane pieces). The

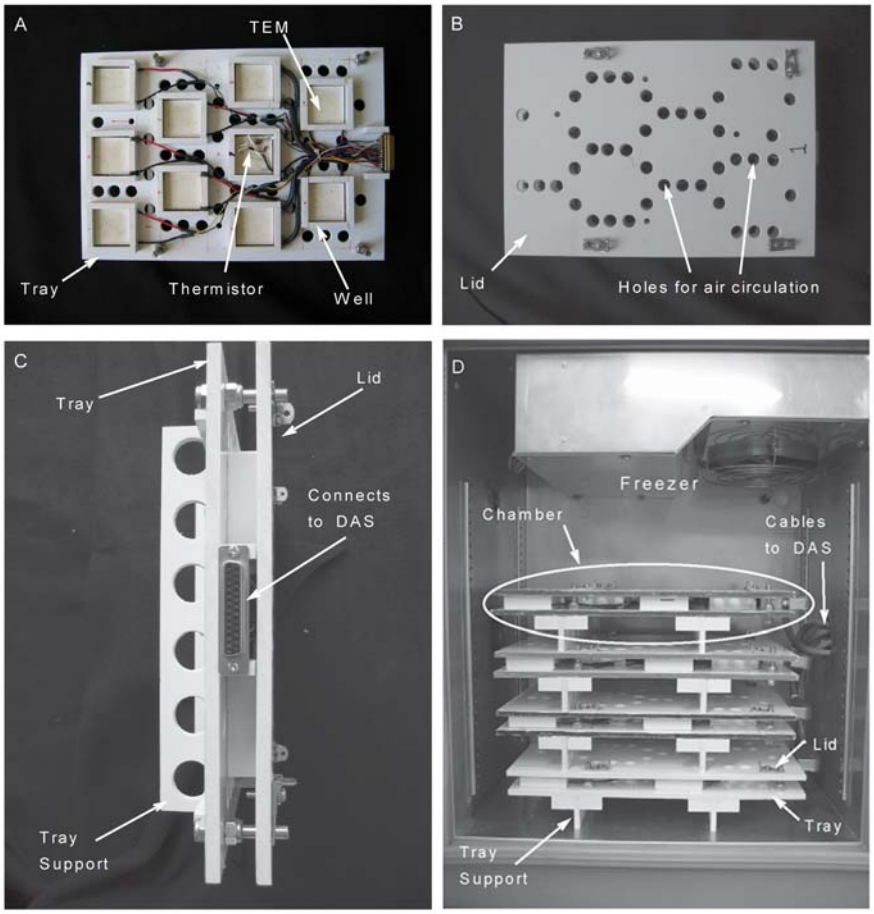

Figure 1 Layout and design of the chambers used for cold-hardiness evaluation. Each chamber consists of (**A**) a tray with 10 wells containing thermoelectric modules (TEM), where four to five buds or two to three cane pieces are placed and (**B**) a lid that when tightened ensures close contact between sample and TEM. The data acquisition system (DAS) is connected to (**C**) the cold-hardiness chamber in the freezer, where up to four chambers (**D**) can be run simultaneously.

freezer was programmed to hold at 4°C for 1 hr, drop to -40°C in 11 hr (a cooling rate of 4°C/hr), hold at -40°C for 1 hr, then return to 4°C in 10 hr (a warming rate of 4.4°C/hr). The DAS recorded signals from each TEM at 15-sec intervals and downloaded voltage output directly to Excel. Exotherms were identified manually from a plot of thermistor output (x axis) versus loaded-TEM output minus empty-TEM output (y axis). Lethal temperatures for buds were reported as Bud LTE_{10}, Bud LTE_{50}, and Bud LTE_{90}, the temperatures at which 10%, 50%, and 90% of the buds were killed, respectively (Andrews et al. 1984). These values were determined from the bud exotherm range and distribution that were clearly visible as spikes on each TEM (Figure 2). For canes, lethal temperatures were reported as phloem LTE_{10} and xylem LTE_{10}. These values were determined by assuming the first range of small exotherms just below -10°C indicated death of phloem cells and the larger exotherms as the temperature continued to decline (Figure 2) indicated death of xylem parenchyma and pith (Wample et al. 2001). Once these ranges were established, the temperatures at which 10% tissue damage occurred were then estimated for each TEM.

Comparison of DTA systems. To test the updated system, bud and cane samples of the same grape cultivar, sampling date, and location were run simultaneously in both systems. Following dissection, 40 buds and 16 cane pieces were thoroughly mixed for each of eight cultivars (see below) and then randomly assigned to one of the two DTA systems with four replicate TEMs each (each TEM containing five buds or two canes). The two systems were run with identical temperature regimes (as described above) on each sampling date. This test was conducted from January through March 2005, as grapevines progressed from maximum cold hardiness to approaching budbreak, to compare as wide a range of LTEs as possible.

Relationship between LTE and cane damage. Cane exotherm output of the updated DTA system was also compared with tissue browning (indicating tissue death). Because exotherms in cane tissues are more difficult to interpret than bud exotherms (Wample et al. 2001), it was important to confirm the accuracy of our TEM interpretation. Dormant canes from field-grown Chardonnay and Cabernet Sauvignon were collected on 9 March 2005, as described above. A portion of the canes were stored in a 2°C cooler and held for tissue damage verification following LTE analysis. Two internode pieces from the fourth to seventh nodes were placed on each of four TEMs (four replicates). The freezer was programmed for the standard 4°C/hr decline and LTE analysis was performed. Using the critical temperatures established from this LTE analysis, the remaining canes were exposed to a 4°C/hr cooling rate and then removed at the temperatures where LTEs indicated phloem and xylem damage (expected damage). Twelve two-bud cane pieces for each damage level (no damage, 20% phloem damage, 100% phloem damage, 20% xylem damage, and 50% xylem damage) were frozen to the predetermined temperatures. The temperature at which 20% damage of phloem and xylem occurred was used rather than the 10% damage (LTE_{10}) normally reported in order to ensure consistent damage. After freezing, the canes were allowed to set at room temperature for 24 hr, and then sectioned to confirm tissue browning visually (Figure 3), as described by Andrews et al. (1984). One cross-section in the internode area of each cutting was made, and the fraction of brown tissue compared with the total surface area was estimated using a scale of zero (0% damage) to 10 (100% damage). The observed damage (determined from tissue browning) and expected damage (determined from exotherm output) were compared using χ^2 analysis.

Effect of surface moisture on freezing. The influence of surface moisture on cold injury of bud and cane tissues was tested by performing LTE analysis on dormant canes collected on 15 March 2005 from field-grown Cabernet Sauvignon as described above. Canes were cut into three-bud sticks, and ends were sealed with household paraffin to prevent desiccation from or water infiltration through the cut ends. The canes were then assigned one of three treatments with 10 canes in each. The dry treatment was sealed in a plastic bag with drierite (W.A. Hammond Drierite Co., Xenia, OH), while the moist and untreated treatments were sealed in plastic bags. All three were stored in a 2°C cooler for 48 hr. One hour before samples were prepared for LTE analysis, the moist treatment was misted with water applied by a hand sprayer then held in the sealed plastic bag in the 2°C cooler. Low temperature exotherm analysis was performed as described above using four replicate TEMs per treatment.

Comparison of cultivars. Once it was established that the two systems were detecting exotherms at essentially the same temperature (Figure 4), data from both systems were combined to compare the seasonal bud and cane LTEs of selected winegrape cultivars. Samples were collected as described above from mature (>20 years old), own-rooted, field-grown, spur-pruned *V. vinifera* cvs. Riesling, Chardonnay, Cabernet Sauvignon, Merlot, and Malbec located at the Washington State University Irrigated Agriculture Research and Extension Center in Prosser (46°17′N; 119°44′W; elevation 270 m; for vineyard details see Keller et al. 2005) and from Viognier, Pinot gris, and Syrah located at adjoining vineyards with similar soil and management conditions. All eight cultivars had been run weekly in the standard system starting in Nov 2004, so data were available for the entire season. For each cultivar, four replicate TEMs with five buds each (20 buds total) and four TEMs with two canes each (eight cane pieces total) were run for each sample date as described above.

Data analysis. Statistical analyses were carried out using the Statistica software package (version 7.0; StatSoft, Tulsa, OK). Data for system comparison were tested using

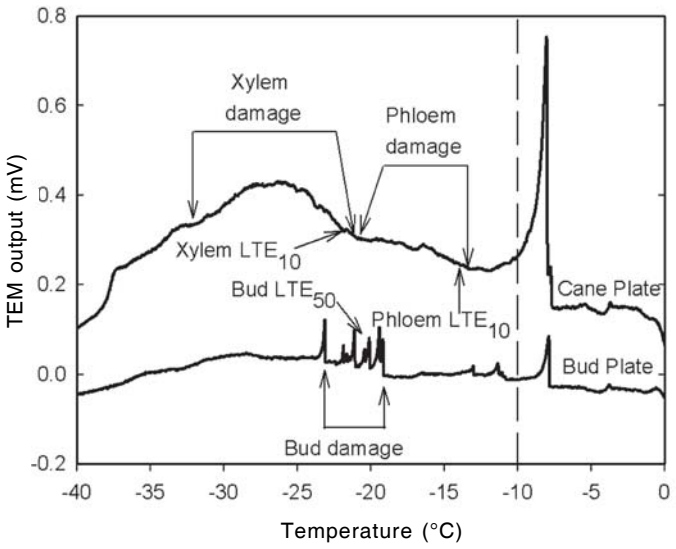

Figure 2 Typical DTA profiles of low temperature exotherms (LTE), indicating lethal intracellular freezing, from two single TEM containing either five buds (lower plot) or two cane pieces (upper plot) of Malbec sampled on 23 Feb 2005, in Prosser, WA. High temperature exotherms (HTE), indicating nonlethal extracellular freezing, are shown to the right of the dashed -10°C line.

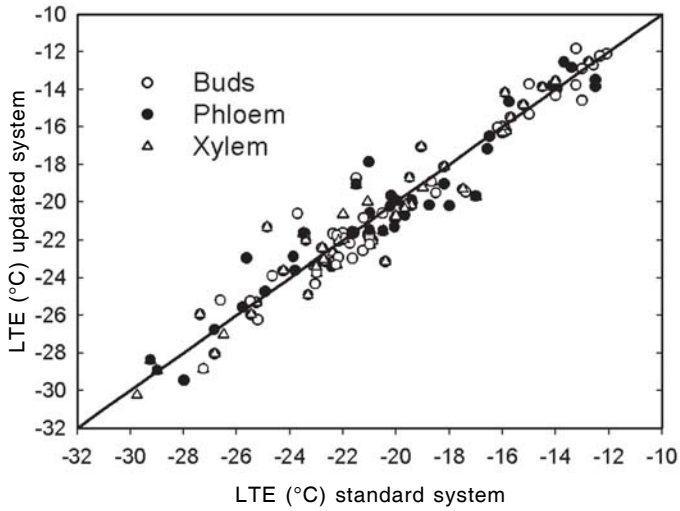

Figure 4 Relationship between low temperature exotherm (LTE) values obtained using duplicate bud and cane samples collected from eight *V. vinifera* cultivars between January and March 2005 and run simultaneously on the standard and the updated DTA system for cold-hardiness evaluation. Each data point represents the mean output of four TEMs containing either five buds or two cane pieces each ($r = 0.92$, $p < 0.001$, $n = 113$).

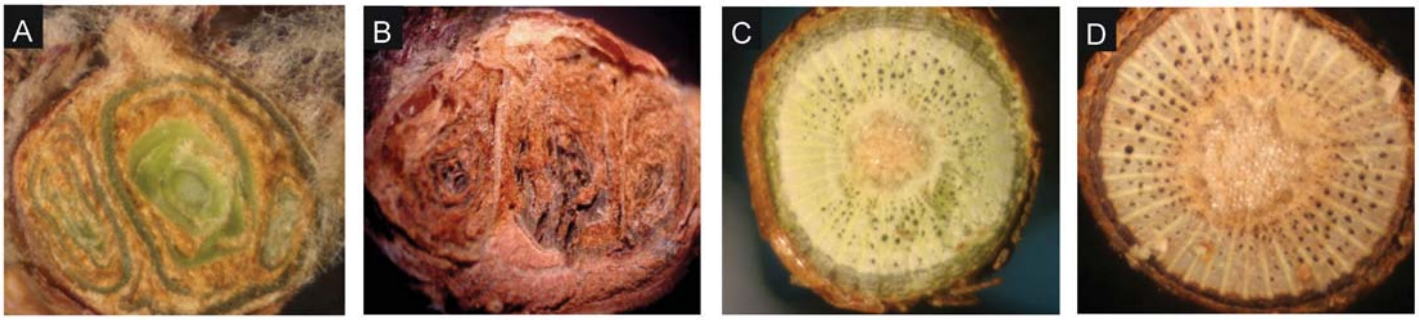

Figure 3 Cross sections of (**A**) uninjured grapevine composite bud, (**B**) bud killed by lethally low temperature, (**C**) cane with approximately 20% freezing-induced phloem injury, and (**D**) cane with 100% freezing-induced xylem injury.

regression analysis. Data for cultivar comparison and the surface moisture experiment were tested using one-way analysis of variance. Duncan's new multiple range test was performed for post-hoc comparison of means.

Results and Discussion

Interpretation of exotherm patterns. A representative DTA profile (exotherm pattern) from the updated system for cold-hardiness evaluation, in this case using Malbec buds and canes, is shown in Figure 2. The HTEs between -5°C and -10°C are associated with nonlethal freezing of extracellular water (Andrews et al. 1984). Bud LTEs between -19°C and -24°C correspond to intracellular ice formation, which results in lethal bud damage. The 5°C range over which these bud exotherms occurred clearly shows that not all buds freeze at the same temperature. This LTE range was generally wider (3°C to 7°C) during the acclimation and deacclimation periods in fall and spring, in contrast to a narrower range (2°C to 3°C) in winter when buds were fully acclimated. Phloem and xylem LTEs were much less pronounced than the bud LTEs, which is consistent with previous findings (Wample et al. 2000) and generally makes interpretation of cane damage difficult. Phloem damage was associated with the bumps between -14°C (injury beginning) and -18°C (injury complete; no live phloem tissue), whereas xylem damage began at ~ -22°C and was complete (no live xylem parenchyma) at ~ -32°C (Figure 4). The "fuzzy" nature of these exotherms necessarily makes interpretation somewhat subjective and requires a skilled operator for consistent results (see the discussion below on the relationship between LTE and cane damage).

Comparison of DTA systems. The two systems closely agreed (Figure 4); the slope of the regression line was not significantly different from 1.0. This confirms that the updated system detected exotherms at the same temperatures as the standard system. Therefore, cold-hardiness values obtained with the updated system may be directly compared with those from the standard system. However, the updated system was much more efficient and user-friendly, since it was far easier to operate, permitted a more rapid sample throughput, was physically more compact, and allowed direct data transfer to Excel which streamlined the data analysis.

Relationship between LTE and cane damage. Chardonnay and Cabernet Sauvignon had a small amount (5 to 8%) of phloem damage before being subjected to DTA analysis (Table 1), which may have been caused by a slight freeze before sample collection or by mechanical injury. Not all canes showed phloem injury at exactly the same temperature. Similar to the buds, the range of phloem LTE_{10} was broader in the fall and spring (≤7°C) than it was during midwinter (≤3°C). However, as expected, the severity of cold injury increased as temperature declined (Table 1). There were only minor differences between expected damage and observed damage, indicating that actual extent of phloem and xylem injury coincided with damage predicted from the interpretation of LTEs. For instance, Chardonnay showed no xylem damage at -17°C but showed 20 to 30% damage at -18°C, regardless of measurement protocol. One exception occurred with Cabernet Sauvignon at -20°C, where only 80% phloem damage was observed even though LTE analysis predicted 100% damage. Nevertheless, considering the general difficulty of interpreting cane exotherms (see Figure 2), the overall agreement between expected and actual injury levels (Table 1) confirmed that reliable data can be consistently obtained by a trained operator.

Table 1 Comparison of low temperature exotherm (LTE) analysis (expected damage) and tissue browning (observed damage) of phloem and xylem tissues of grapevine canes collected on 9 March 2005 in Prosser, WA.

		Phloem damage (%)			Xylem damage (%)		
	Temp (°C)[a]	Expected[a]	Observed[b]	Signif[c]	Expected[a]	Observed[b]	Signif[c]
Chardonnay							
	+2	0	5	*	0	0	ns
	-14	20	14	ns	0	0	ns
	-17	100	95	ns	0	0	ns
	-18	100	94	ns	20	30	ns
	-26	100	100	ns	50	57	ns
Cabernet Sauvignon							
	+2	0	8	*	0	0	ns
	-17	20	21	ns	0	0	ns
	-20	100	80	*	0	0	ns
	-23	100	100	ns	20	28	ns
	-28	100	100	ns	50	63	ns

[a]Temperature and corresponding expected damage determined using LTE analysis.
[b]Observed damage determined from visual evaluation of frozen cane samples following LTE analysis.
[c]Mean ($n \geq 4$) differences tested by χ^2 analysis; * and ns significant at $p = 0.05$ or not significant, respectively.

Effect of surface moisture on freezing. Bud LTEs occurred over a range of -14°C to -19°C in the moist treatment and a range of -15°C to -22°C in the untreated samples (Table 2). The LTEs in the dry treatment ranged from -18°C to -23°C and were small because of the lower moisture content of the bud tissues. On average, surface moisture raised the temperature at which bud LTEs occurred by 1°C to 2°C when compared with the untreated buds and by 3°C to 4°C when compared with the dry buds (Table 2). This is consistent with earlier results obtained under different conditions (Johnson and Howell 1981, Wolf and Pool 1987). The LTEs for phloem and xylem damage were similar for the untreated and moist samples but were about 2°C lower in the dry canes. Additionally, the greater amount of extracellular water in the moist samples led to high HTEs (~ -5°C) that were not detectable in the untreated and dry samples, which is in agreement with findings by Wolf and Pool (1987).

The present data confirmed that moist buds and canes may be damaged at a higher temperature than dry buds and canes. This may happen when the minimum temperature (at dawn) coincides with the presence of heavy dew. These results emphasize the importance of not allowing samples to dry out before and during LTE analysis. A temperature difference of 2°C in the vineyard could be the difference between live and dead buds. Thus a false LTE value could result in a grower waiting too long to start frost control, resulting in more bud and cane injury than expected.

Comparison of cultivars. Bud cold hardiness of all cultivars tested increased with the overall trend of declining temperatures from November through January, after which the buds began to deacclimate and gradually lost cold hardiness (Figure 5). The white winegrape cultivars were generally hardier in midwinter than their red counterparts. They also showed more pronounced cultivar differences in bud LTE_{50} throughout the dormant season (Figure 5B). Riesling was clearly the hardiest of all cultivars tested; while Chardonnay matched Riesling in midwinter, it was much less hardy in fall and late winter. Neither Riesling nor Chardonnay was able to regain hardiness levels in mid-March once deacclimation was underway. Bud hardiness of Pinot gris was similar to that of Viognier. Both of these cultivars were pruned in early March, so we were unable to follow their deacclimation patterns into late March. However, after midwinter their bud LTE_{50} closely traced those of Chardonnay, which tends to deacclimate early and quickly. Viognier and Pinot gris may also be susceptible to late spring frosts, which should be confirmed with further investigation.

Among the red winegrape cultivars, Syrah and Malbec buds were at least as hardy (based on bud LTE_{50}) if not hardier than Merlot buds through the entire season (Figure 5A). Both Syrah and Malbec attained midwinter hardiness values as low as Cabernet Sauvignon but appeared to lose hardiness more rapidly in the spring, indicating they could be sensitive to spring frosts similar to Merlot. By mid-March all four cultivars were deacclimating as a result of the warming temperatures, but only Cabernet Sauvignon regained hardiness levels during a cooling period. Phloem and xylem LTEs (data not shown) showed similar trends and cultivar differences as those observed with buds. Again, among all *V. vinifera* cultivars, Riesling was very hardy in terms of cane phloem and xylem. Compared with the other cultivars, Riesling LTEs were ~ 3°C lower in fall, up to 6°C lower in midwinter (phloem LTE_{10} = -22°C in early January), and 1°C to 2°C lower during the deacclimating phase beginning in late February. In contrast, Cabernet Sauvignon canes were relatively slow

Table 2 Effect of surface moisture on low temperature exotherms (LTE in °C) of buds and canes of Cabernet Sauvignon grapevines sampled on 15 March 2005 in Prosser, WA.

Treatment	Bud LTE_{10}	Bud LTE_{50}	Bud LTE_{90}	Phloem LTE_{10}	Xylem LTE_{10}
Untreated	-15 a[a]	-20 b	-22 b	-12 a	-19 ab
Dry	-18 b	-21 b	-23 c	-14 b	-20 b
Moist	-14 a	-18 a	-19 a	-12 a	-18 a

[a]Means within columns followed by the same letter do not differ significantly at $p = 0.05$ by Duncan's new multiple range test.

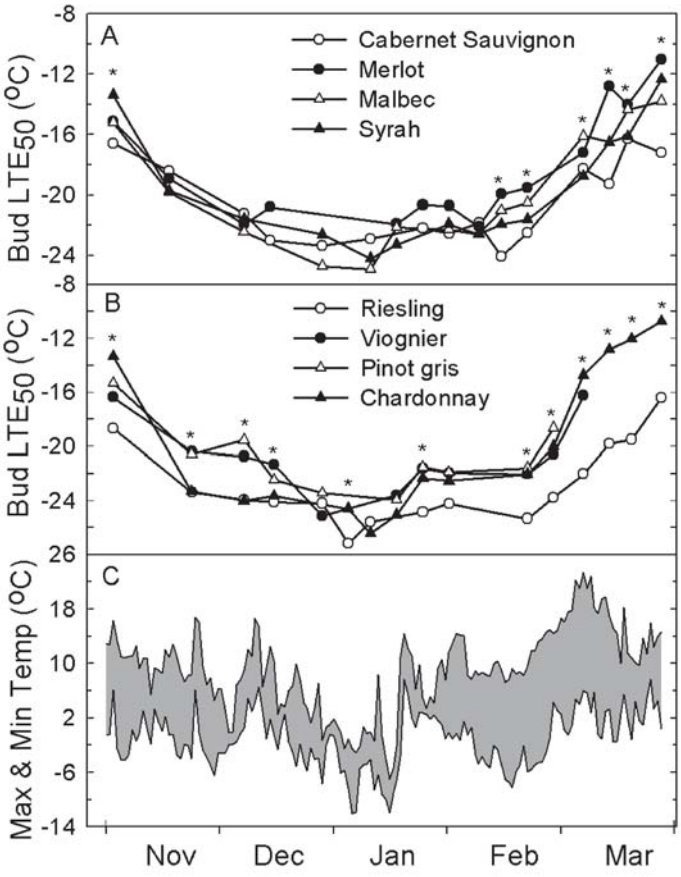

Figure 5 Bud cold hardiness (based on LTE_{50}) of eight *V. vinifera* cultivars from November 2004 through March 2005 in Prosser, WA. Red winegrape cultivars (**A**), white winegrape cultivars (**B**), and daily maximum and minimum temperature (**C**). Asterisk (*) indicates dates at which differences in LTE_{50} were significant at $p \leq 0.05$ (n = 4).

to harden off in the fall and were similar to the other cultivars through winter, but it was the only cultivar that matched Riesling during the deacclimation period.

These preliminary results suggest that buds and canes of Syrah, Malbec, and Pinot gris can withstand similar winter temperatures as the more established cultivars. In particular, fears that Malbec may not be able to survive typical winter temperatures in eastern Washington appear to be unfounded. However, the present results were obtained with >20-year-old vines. Although it seems unlikely, we cannot exclude the possibility that young vines might differ in their cold acclimation/deacclimation pattern and midwinter hardiness. There is a fair amount of published data on seasonal bud LTE_{50} values of the commonly grown cultivars—Cabernet Sauvignon, Chardonnay, and Riesling (Hamman et al. 1996, Proebsting et al. 1980, Wample et al. 2001, Wolf and Cook 1994)—which compare closely with our results on these cultivars given climatic differences among regions and seasons. There has been far less research conducted on seasonal cane hardiness. However, the present phloem and xylem LTE_{10} values on Cabernet Sauvignon and Chardonnay do compare closely with those reported by Wample et al. (2001). Cabernet Sauvignon, Chardonnay, and Riesling are excellent cultivars to be used as standards in future grape cold-hardiness research when testing potential new cultivars for areas prone to cold damage.

Conclusion

A cold-hardiness evaluation system has been developed that offers an improvement in DTA design. The whole process was simplified, while at the same time providing reliable and accurate identification of critical temperatures for dormant grapevine buds and canes. This updated system and method could be applicable to other studies dealing with cold injury and cold hardiness of woody plants. A further improvement would be the development of macros in Excel that would automatically process the output and create graphs to minimize postprocessing of data.

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