Measurement of Hard Vitreous Kernels in Durum Wheat by Machine Vision[1]

S. J. Symons,[2,3] L. Van Schepdael,[2] and J. E. Dexter[2]

ABSTRACT

Cereal Chem. 80(5):511–517

An imaging method that detects nonvitreous regions in sound kernels of durum wheat at high speed is described. Kernels are analyzed simultaneously for individual vitreousness and individual kernel size and shape are measured concurrently. The measurement of 500 kernels per sample is adequate for highly reproducible results. Significant agreement was found between inspector-determined hard vitreous kernel percentages (HVK) and machine-determined HVK scores for export cargo samples of Canadian Western Amber Durum (CWAD), with differences between the two methods of typically ±3%. For railcar samples of CWAD taken on delivery to the terminal, agreement between inspector-determined and machine-determined HVK scores were more variable. The variability between the two methods generally increased as the HVK score of the sample became lower. For inspector-determined HVK scores of <50%, difference between inspector and machine HVK scores for some samples was substantial. Such large differences are partially attributable to the way in which weathered kernels are assessed. Weather-damaged kernels were frequently classified as nonvitreous by the machine system due to disruption of the enveloping tissues, whereas inspector evaluations often classify weather-damaged kernels as vitreous. The speed, accuracy, and reproducibility of the machine methodology gives it enormous potential as a replacement for visual inspection of CWAD for HVK in Canadian grain terminals.

The proportion of hard vitreous kernels (HVK) in a sample is an internationally recognized specification determining the value of durum wheat (*Triticum durum* Desf.). In general, vitreous durum wheat kernels are higher in protein content than nonvitreous kernels (also referred to as yellow berry, mealy, or starchy kernels) (Dexter et al 1989). Protein content is the primary factor associated with pasta texture (Feillet and Dexter 1996). However, as the use of minimum protein guarantees in durum wheat trade has increased due to the development of NIR as a rapid protein testing procedure, the relevance of HVK in ensuring adequate pasta cooking quality has decreased (Dexter and Edwards 1998).

A characteristic of vitreous durum wheat kernels of continuing commercial importance is that they are harder than nonvitreous kernels (Dexter et al 1988). Hardness is a desirable attribute for durum wheat milling because semolina, a coarse-milled product suitable for pasta or couscous manufacture, is more highly valued than durum wheat flour (Feillet and Dexter 1996). As HVK content declines, kernel texture becomes softer, leading to lower semolina yield (Bolling and Zwingelberg 1972; Matsuo and Dexter 1980; Dexter and Matsuo 1981; Sissons et al 2000).

HVK is a primary specification for Canadian Grain Commission (CGC) durum wheat grades and is used to ensure semolina milling yield potential. The grades No. 1 Canada Western Amber Durum (CWAD), No. 2 CWAD, and No. 3 CWAD have minimum hard vitreous kernel (HVK) requirements of 80, 60, and 40%, respectively (CGC 2001).

Vitreous and nonvitreous kernels are currently identified visually in the Canadian grain inspection system. Vitreous kernels appear as translucent amber due to a tightly compacted internal structure, whereas nonvitreous kernels are opaque or contain opaque regions because endosperm structure is less compact with open spaces (Dexter et al 1989). The CGC HVK procedure involves manual separation of vitreous and nonvitreous kernels similar to standard methods of the International Association for Cereal Science and Technology (ICC 1995) and International Organization for Standardization (ISO 1980). Partially vitreous (piebald) kernels with a nonvitreous zone of any size are considered nonvitreous. The method is somewhat subjective and is tedious. Bottlenecks can occur at high throughput grain elevators when the primary grade determinant is HVK.

Rapid, accurate, and precise machine vision methods for grain classification and grading are major research priorities at the CGC. Sapirstein and Bushuk (1989) and Shatadal et al (1998) explored the possibility of measuring light transmission of durum wheat by digital image analysis to rapidly and objectively estimate durum wheat HVK. In this article, we describe a machine vision system that classifies durum wheat kernels on a kernel-by-kernel basis as vitreous or nonvitreous according to translucency. The method shows great promise as an aid or replacement to the visual CGC HVK procedure.

MATERIALS AND METHODS

Durum Wheat Samples

Cargo samples were official CGC samples taken during loading of CWAD cargoes at terminal elevators in Vancouver, Thunder Bay, and several elevators on the St. Lawrence River. Official samples ensure random sampling and overall representation of large commercial volumes of grain.

CWAD railcar lots arriving at terminal elevators in Thunder Bay, ON, were selected by CGC grain inspectors to obtain a sample set with a wide range of HVK. Composite samples containing 10 railcar lot samples each were prepared to give HVK near 40, 50, 60, 70, 80 and 90%.

Cargo and railcar samples were taken over two crop years (1994, 1995) and represent a mixture of registered cultivars, growing and storage conditions, and quality-grading factors.

CWAD kernels used to train the machine vision system were manually separated by a senior grain inspector (Industry Services Division, CGC, Winnipeg) into vitreous, piebald, and starchy segregates. Samples were selected from hundreds of railcar samples collected during inward inspection in Thunder Bay. To ensure the greatest possible kernel variability during training, no more than 50 kernels (a single image) were used from a single railcar sample, and often, an image was composed of kernels from several railcar samples. Care was taken to ensure that kernel segregations were made from samples with a wide range of HVK values, to account for any possible influence of sample quality on kernel characteristics.

Wheat Characterization

Visual determination of HVK. All visual HVK values were determined by CGC grain inspectors at grain terminals at the time of railcar discharge or cargo loading. The CGC HVK procedure (CGC 2001) defines hard vitreous kernels as "whole or broken,

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[1] Grain Research Laboratory manuscript no. 845.

[2] Canadian Grain Commission, Grain Research Laboratory, Winnipeg, MB, R3C 3G8 Canada.

[3] Corresponding author. E-mail: ssymons@grainscanada.gc.ca. Phone: +1-204-983-5302. Fax: +1-204-983-0357.

Publication no. C-2003-0723-04R.

reasonably sound kernels that show clear evidence of vitreousness, even though they may be bleached". Nonvitreous samples are defined as "having a starch spot of any size, damaged kernels (sprouted, rotted, severely frost damaged, etc.) and kernels of wheat from other classes, i.e. common wheat".

A Boerner-type divider was used to divide a representative 250-g subsample from a cleaned sample. The representative portion was sieved over a No. 4.5 slotted sieve. Material that passed through the sieve was not used in the HVK determination. From the material that remained on top, a 15-g sample was divided for railcar lots, and a 25-g sample was divided for export shipments. Vitreous and nonvitreous kernels were separated. Bleached (weathered) kernels were cut and the endosperm examined to determine whether they were vitreous. Vitreous and nonvitreous portions were weighed and HVK was expressed as percentage by weight of vitreous kernels.

Single Kernel Characterization System (SKCS). An SKCS 4100 (Perten Instruments, Springfield, IL) was used to characterize 300 kernels of each sample according to the operating manual. Determinations were performed in duplicate in randomized design. The SKCS 4100 gives values for kernel weight, kernel diameter, moisture content, and hardness index, but only hardness index results are reported.

Milling. Lots (1 kg) of each composite sample were conditioned to 16.5% moisture overnight and milled in a climate-controlled room (21°C, 60% rh) with a four-stand Allis-Chalmers mill in conjunction with a laboratory purifier (Black 1966), using the mill-flow described by Dexter et al (1990).

Machine Vision System

Instrumentation. The KS400 imaging software package (Carl Zeiss Vision GmbH, Hallbergmoos, Germany) was used for machine vision. The machine vision application for HVK analysis was programmed in the KS macro language. A Meteor II framegrabber (Matrox, Montreal, Canada) provided the interface to a monochrome instrumentation NC-70x camera (Dage-MTI, Michigan City, IN) fitted with a 60-mm macro lens (Carl Zeiss, Germany). The camera and lens were mounted on an Illuma light table (Bencher, Wood Dale, IL) to capture transilluminated kernel images. The intensity of the substage lamp (600W) was controlled through a vario-stat and the 120V power supply smoothed with a Sola (type CVS harmonic neutralized 3,000 VA) constant voltage transformer. Baffles in the light table only allowed light reflected from the sides of the lamp chamber to impinge on the kernels. Samples of 50 transilluminated kernels were imaged from a surface of 9 × 10 cm. The camera height and focus were adjusted to completely fill the image frame with the sample field with the kernels in sharp focus. This was fixed for the duration of this project.

Calibration procedure. The hardware calibration KS macro allowed interactive adjustment of both camera and frame-grabber amplifier parameters to obtain a consistent and reproducible image-grabbing system. Using a calibrated Kodak photographic step tablet (Kodak Cat # 152 3422), camera gain and brightness controls were manually adjusted so that designated grey steps were set as the white and black points of the system. The frame-grabber amplifiers were then manually adjusted through software controls to linearize the grey step response. These steps were repeated until a smooth linear response was achieved. Fluctuations in the light source intensity were due to voltage variation. This prevented accurate calibration. The Sola constant voltage transformer eliminated this source of error. Although this calibration process took up to 1 hr to complete, the method was reliable and reproducible. Future developments could include automation of this process using direct camera control through a software interface. Calibration gave grey step measurements within ±1 grey value with the stabilized light source.

Training and classifier development. The training macro was designed to grab images of known kernel types (vitreous, piebald, or starchy), and provide simple software control for the development of linear Bayesian classifiers, either as part of a fully automated HVK analysis process or as a stand-alone calibration process. The tasks were to grab images, measure features, create a training database, create the classifier, and test the classifier using training images. A second test phase using an independent set of images of single HVK types was run using the sample analysis mode.

Kernels were individually classified according to translucency by measuring densitometric and Haralick texture features available in the KS software. These features were used in the classifier functions provided in KS to develop a linear classifier based upon Bayes' Theorem, Mahalanobis distance, or *k* nearest neighbor. The three modeling approaches were used to independently validate the classifier model developed. The Bayes Theorem classifier was used in the HVK software macro. In KS, this classifier is applied directly to the image at the point feature values are determined, resulting in real-time classification. Cross-validation gave 95% or higher correct classification in the training data set.

A second linear Bayesian classifier was later added to segregate the kernels classified as piebald into three categories: high-piebald (≥75% starchy endosperm), medium-piebald (≥10% < 75% starchy endosperm) and low-piebald (≤10% starchy endosperm). For the development of this classifier, piebald images obtained during the original training phase were used. Images were displayed and kernels interactively tagged with an ID for each piebald category. The category for each kernel was visually determined by a single operator to ensure consistency of interpretation against predetermined criteria.

Sample analysis. For analysis, sets of 50 kernels were randomly placed into the image window and quickly checked to ensure that no kernels were touching. Kernel orientation had minimal effect on the prediction of HVK unless the kernels were thin or damaged. Ten images of 50 kernels each generated CV of typically 6–12% for railcar samples and 4–8% for cargo samples. For each sample, all the images were stored, allowing reestimation of HVK scores with other classifiers that were developed throughout the duration of this work.

Verification of machine vision identification. Twenty-three railcar samples were selected where the machine vision determination of

TABLE I
Semolina Milling Summary for Composites of Durum Wheat Samples[a,b]

V-HVK[c] (%)	SKCS HI[d]	Semolina Yield (%)	Flour Yield (%)	Milling Yield (%)	Coarse Middlings (g)	Product to Sizing (g)
40.7	89.1	66.6	9.0	75.3	780	255
49.9	93.7	66.7	7.7	74.4	773	264
59.8	96.0	68.2	7.8	75.4	797	269
70.2	97.1	68.1	7.6	75.7	791	273
80.0	97.7	68.7	7.4	75.7	803	286
90.1	98.4	68.2	6.9	75.1	800	294

[a] Results from single 1-kg millings. Semolina, flour, and total milling (semolina and flour combined) yields expressed as proportion of clean wheat on constant moisture basis. Coarse middlings and product to sizing expressed on as-is weight basis.

[b] Each prepared from 10 individual railcar lots of comparable HVK to give a range from 40 to 90%.

[c] Mean value of visually determined HVK values for 10 component railcar lots.

[d] Single Kernel Characterization System hardness index. Mean of triplicate determinations. Standard error 1.3 units.

HVK differed from the visual determination by 10% or greater. Each sample of 50 g was manually separated into starchy, vitreous, and piebald kernels. Additionally, kernels were also assigned to bleached, damaged, wheats of other classes, and foreign material. Each fraction was subsequently assessed using the machine vision system to evaluate the effect of each factor upon classification.

Each whole sample was also manually separated on the basis of machine vision classification into starchy, piebald, and vitreous kernels. Each of these fractions was subsequently manually inspected and segregated into the three categories above. This allowed a cross-validation of the HVK methods.

Statistics

Statistical analysis was performed using v. 6.12 of SAS (SAS Institute, Cary, NC).

RESULTS AND DISCUSSION

Hardness and Milling Characteristics of Railcar Lots of Variable HVK

Semolina milling results of composites of railcar lots clearly demonstrated the impact of HVK on durum wheat milling potential (Table I). Total milling yield (semolina and flour combined) was not affected by HVK but there were clear trends toward higher semolina yield and lower flour yield as HVK increased. Also, the yield of coarse middlings sent to the purifier from the break passages (the source of semolina) and the total amount of product sent to the first sizing passage (coarsest material from initial purifications) increased as HVK increased. The single kernel characterization system (SKCS) hardness index (HI) values increased with HVK, indicating increased grain hardness. These results were in agreement with numerous previous reports that have concluded that the softer texture of nonvitreous kernels compared with vitreous kernels reduces durum wheat semolina milling potential of durum wheat (Matweef 1963; Menger 1971; Bolling and Zwingelberg 1972; Matsuo and Dexter 1980; Dexter and Matsuo 1981; Dexter et al 1988, 1989; Dexter and Edwards 1998; Sissons et al 2000).

Recently, Sissons et al (2000) reported that HI determined by the SKCS correlated to HVK and had potential as a durum wheat semolina milling predictor. Previous attempts by Dexter et al (1988) to estimate HVK by hardness using the particle size index (PSI) test were not successful. PSI was strongly correlated to HVK and to hardness-related semolina milling factors such as break release and energy consumption during roller milling, but the PSI range was too small to allow meaningful segregation of durum wheat according to hardness.

In the current study, there was a definite positive trend between SKCS HI and HVK for the composite samples prepared from durum wheat railcar lots (Table I), and the mean SKCS HI values for the railcar lots within each composite (Table II). However, the overall range of HI was too narrow to reliably segregate railcar lot composites according to HVK at ≈10% intervals, particularly once HVK reached 60% and above. Furthermore, HI values for individual railcar lots exhibited overlap over an HVK range of 40% (maximum HI value 92.15) to 80% (minimum HI value 91.70), making SKCS HI of little value in classifying durum wheat railcar lots according to HVK.

The difficulty in predicting durum wheat by HVK on the basis of hardness is due to the inclusion of partially starchy (piebald) kernels in the nonvitreous category within CGC grade definition (CGC 2001), in agreement with international standards (ICC 1995; ISO 1980). Piebald kernels are almost as hard as fully vitreous kernels (Dexter et al 1989). Therefore, the inferior milling quality of durum wheat as HVK declines is due almost exclusively to the presence of fully starchy kernels. Matweef (1963) proposed fully starchy kernels be given more emphasis than piebald kernels when visually estimating durum wheat vitreousness. Technologically, this proposal is a valid view shared by others (Menger 1971; Dexter et al 1988; Sissons et al 2000).

TABLE II
Single Kernel Characterization Hardness Index Values for Durum Wheat Railcar Samples[a]

V-HVK Range	HI Mean	HI Range	HI SD
40.0–42.0	88.31	82.04–92.15	2.72
48.0–51.9	92.25	88.42–96.91	2.64
58.0–60.0	94.14	90.16–98.15	2.29
69.8–71.8	93.87	90.93–97.48	2.19
80.0–80.0	96.00	91.70–100.45	2.98
88.6–91.0	97.51	96.11–100.08	1.39

[a] Ten railcar lot samples in each V-HVK range. SKCS HI determined singly on each railcar lot sample.

Classification of Vitreousness by Machine Vision

HVK is an internationally well-established visual durum wheat quality standard and, regardless of the merit of classifying durum wheat by hardness, HVK continues to be used as a standard for durum wheat trade. A machine vision system that classifies durum wheat kernels according to degrees of vitreousness would emulate the visual HVK method while eliminating the problems of subjectivity and tediousness associated with visual HVK. Additionally, a machine vision system may have the potential to predict milling quality using HVK measurements. To be effective as a durum wheat semolina milling predictor, a machine vision system should

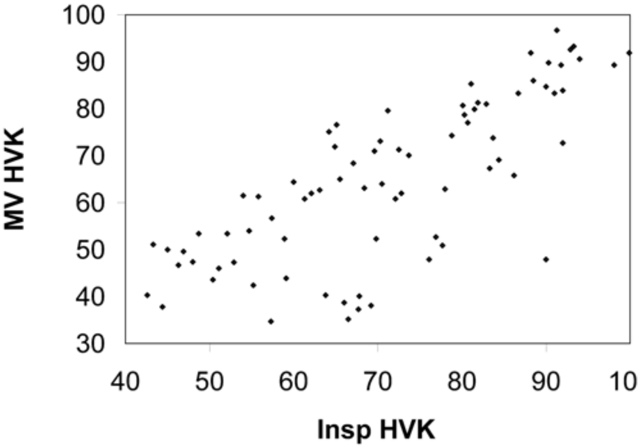

Fig. 1. Comparison of machine vision (MV) to visual (Insp) HVK scores for 79 railcar samples of durum wheat entering Thunder Bay, ON.

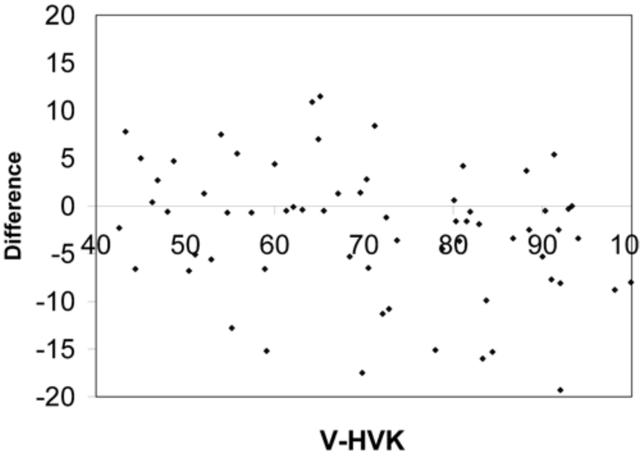

Fig. 2. Difference between machine vision (MV) and visual (V) inspection values for HVK scores for 79 railcar samples of durum wheat from 40 to 99% HVK.

be able to detect partially vitreous kernels and incorporate these into a more meaningful vitreousness score that directly relates to milling quality.

Machine vision differed from visual inspection in that objective criteria including internal kernel characteristics that influence translucency were used to classify individual kernels. Over a range of V-HVK scores on railcar unload samples, there was reasonably good agreement between MV-HVK and V-HVK (Fig. 1). When the disagreement between V-HVK and MV-HVK was >10%, MV-HVK tended to underestimate the V-HVK score (Fig. 2).

Of 79 samples measured, there were 23 with differences >10% between V-HVK and MV-HVK determinations. To evaluate why MV-HVK typically scored lower than V-HVK, a series of kernels derived from these 23 samples were visually segregated by senior grain inspectors into starchy, vitreous, and piebald fractions. Each segregation was subsequently reclassified using MV-HVK. There was a very high agreement between the two systems for starchy kernels (Table III), whereas for both vitreous and piebald kernels, there was only ≈50% agreement of the classification category. In both cases, the largest difference was classification to the class below (vitreous to piebald or piebald to starchy). These differences exist as MV-HVK assesses and measures the internal characteristics of each kernel using translucency, detecting any internal endosperm starchy regions, whereas V-HVK, in most instances, only evaluates the external appearance of the kernel. The overall impact on commercial HVK score, where only vitreous and nonvitreous kernels are considered, using MV-HVK from Table III, is a loss of 45% vitreous kernels to the nonvitreous classes (starchy and piebald) and a 17.3% classification of nonvitreous into the vitreous category with a net 27.7% lowering of HVK score.

Causes of Discrepancies Between MV-HVK and V-HVK Classification

To identify the primary causes for the discrepancy between V-HVK and MV-HVK methods, kernels initially were segregated into vitreous, piebald, and starchy lots by MV-HVK. For each sample, each lot was placed into a separate envelope. Each envelope lot was subsequently reevaluated by a senior grain inspector, who classified each kernel based on appearance. The inspector also identified broken kernels and kernels from wheat classes other than CWAD. Each of the inspector-identified kernels was then once again classified by the MV-HVK software (Table IV, summary of four samples). Vitreous kernels identified by MV-HVK were also selected as vitreous by grain inspectors and this result was confirmed by reevaluation by MV-HVK. The slight misclassification of vitreous kernels into the piebald category was due to instrumental noise. MV-HVK included broken kernels in the

TABLE IV
Machine Vision (MV) Classification of Kernels Initially Classified into Starchy, Vitreous, and Piebald Kernels

Sample		Original MV-HVK	Visual Separation	Reevaluated MV-HVK
164	V	21	21v	18v, 3p
	S	9	3b	3s
			1p	1s
			5s	5s
	P	20	11p	11p
			8b	8p
127	V	20	20v	20v
	S	14	4s	4s
			8b	7s, 1p
	P	16	9v	4v, 3s, 2p
			7b	1v, 3s, 3p
176	V	19	18v	18v
	S	10	6s	6s
			1b	1s
			2p	1s, 1p
	P	21	16p	2v, 14p
			2b	2p
			3v	2v, 1p
334	V	20	19v	17v, 2p
	S	13	4s	4s
			7b	4s, 3p
	P	16	2p	2p
			17b	4v, 4s, 8p

[a] Each fraction was subsequently separated by grain inspectors into grading components as noted; these components reevaluated by machine vision (not all samples shown).

[b] V, vitreous kernels S, starchy kernels P, piebald kernels, b, broken kernels.

TABLE III
Machine Vision (MV) Classification of Kernels Previously Segregated into Starchy, Vitreous, and Piebald Kernels by CGC Inspectors (V-HVK)

	Starchy Class (S) MV Reclassification			Vitreous Class (V) MV Reclassification			Piebald Class (P) MV Reclassification		
Sample	V	S	P	V	S	P	V	S	P
204	0	20	0	118	25	86	8	15	28
273	0	44	9	261	25	128	10	19	34
199	0	47	3	91	38	152	2	34	36
314	0	1	0	238	10	89	13	7	18
350	0	11	4	242	5	120	6	1	19
399	0	77	3	142	20	62	14	22	32
182	1	35	0	147	3	62	6	8	27
194	0	18	1	125	101	179	0	17	5
297	0	15	0	176	24	107	10	16	26
299	. . .	. . .	. . .	263	22	131	7	11	12
164	0	55	4	136	5	89	5	15	53
334	0	9	1	167	40	146	13	23	29
393	0	20	2	92	71	177	10	18	29
408	0	79	0	122	24	62	17	26	38
405	0	9	0	190	30	169	5	2	11
257	0	48	1	127	12	37	33	13	40
225	0	7	1	233	4	112	3	6	17
212	0	34	0	210	12	67	16	11	29
88	0	56	2	101	13	72	7	25	41
140	0	17	0	163	56	137	6	36	26
127	0	13	5	152	33	174	5	5	18
176	0	90	4	134	2	62	14	19	98
22	0	19	1	175	35	88	5	10	13
Total	1	724	41	3,805	610	2508	215	359	679
		94.5%	5.4%	54.9%	8.8%	36.2%	17.2%	28.7%	54.2%

starchy and piebald categories. Broken kernels, which are sound, are treated in the Canadian grading system as vitreous kernels. In the four samples shown in Table IV, there are 11, 15, 3, and 25 broken kernels, respectively, in each 50-kernel sample. While all the broken kernels may not have been sound, this is a major cause of error in lower grade samples. The effects of the break cause light scattering, making the kernels appear opaque, irrespective of endosperm soundness. While in future software revisions, broken kernels could be determined using size and shape characteristics, it was not possible to accurately classify kernel pieces at this time. Further work is planned to improve this aspect of classification.

In some samples, inspectors classified MV-HVK piebald kernels as vitreous. The variability in this classification when kernels were reevaluated using MV-HVK indicates that these kernels were on the borderline of the classification method. Based on experimentation, a small subset of these kernels can change their classification if orientated in a different way on the light table. While this is a source of error, this effect is randomized and minimized by the MV-HVK protocol. Only when the kernels were specifically handled on a kernel-by-kernel basis does this effect influence the predicted result. A second classifier was added in an attempt to minimize this source of error.

Based upon observation, it was noted that weathered kernels, which appear externally starchy, but when cut have a vitreous interior, were primarily classified as starchy by MV-HVK. During visual inspection, inspectors cut open kernels to determine whether the endosperm is vitreous if they are unsure about the kernel type. The machine vision system cannot verify kernels by such a method, although during this study, kernels classified as starchy by MV-HVK were cut if they appeared to be weathered, for validation of the MV-HVK classification. About two kernels in five classified as piebald or vitreous. Weathered kernels are not typically found in the top grades of durum wheat, so this effect on MV-HVK score in the top grades would be minimized.

TABLE VI
Reproducibility of MV-HVK Determination for Durum Wheat Samples Prepared from Railcar Samples to Give an HVK Range of 40–90%

	MV-HVK (5 Reps)		MV-HVK (10 Reps)	
Visual HVK	Mean	CV	Mean	CV
40.7	38.18	5.95	39.9	3.63
49.9	54.2	5.20	53.2	4.60
59.8	62.0	8.40	60.5	5.55
70.2	67.6	4.90	67.6	2.55
80.0	81.5	0.09	80.5	1.80
90.1	87.88	2.72	89.5	1.68

TABLE VII
Repeated Machine Vision (MV) Estimation of HVK Scores for Three Cargo Samples

Sample/ Rep	V-HVK	MV-HVK	Min	Max	CV
I					
A	88.9	91.8	87.8	94	2.21
B		88.3	78	94	5.18
C		85.8	82	92	4.22
Mean		88.6			3.4
II					
A	70.9	57.3	52	62	5.65
B		69.2	64	72.9	5.24
C		77.4	74	81.6	3.24
Mean		68.0			14.8
III					
A	51.8	53.1	46.9	59.2	7.00
B		66.2	62	70	3.86
C		47.1	42.6	56	10.04
Mean		55.5			17.6

[a] Values for three replicates determined from 10 independent samples of 50 kernels.

Thin kernels, which were otherwise sound, were also classified as starchy by MV-HVK. Such kernels, when dissected, had a proportionally very deep crease relative to the width of the kernel. This structure created high internal refraction of the transmitted light, giving the kernel a dark starchy appearance. Again, thin kernels are typically only found in lower grades of wheat.

Samples of lower grade and quality contain higher amounts of broken, weathered, and otherwise damaged kernels. The MV-HVK system, as used, generally misclassified these otherwise vitreous kernels as nonvitreous. Further software development to determine broken kernels and adjust the score would increase MV-HVK scores. Both visual and machine vision systems have their strengths and weaknesses when determining HVK scores.

From a practical point of view, high quality durum samples of high grade and value do not contain damaged, weathered, shrunken, or thin kernels, so MV would be readily applicable in the evaluation of such samples in the grading system.

The other consideration is the repeatability of each method. The same 23 samples were reevaluated both by grain inspectors and by machine vision after a period of 18 months. The MV-HVK estimates on these samples were more consistent with the original evaluation than the visual inspections (Table V). Repeatability and consistency of measurement is of considerable practical importance in trade.

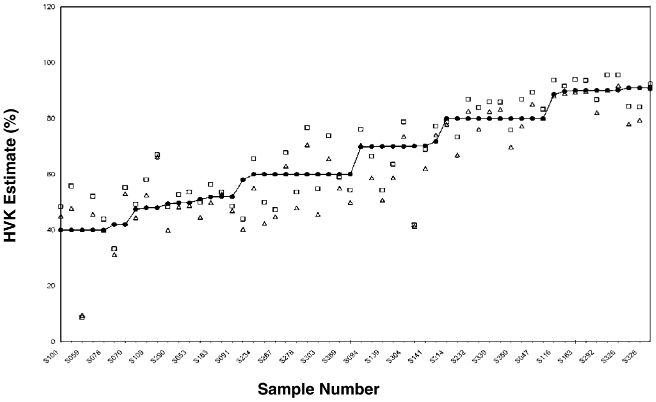

Fig. 3. Comparison of V-HVK scores (●) in inward railcar samples with MV-HVK scores using original vitreous, piebald, and starchy classifiers (Δ) and using a two-step classifier with piebald kernel classification. The low-piebald category has been added to the vitreous category (□) to increase HVK score.

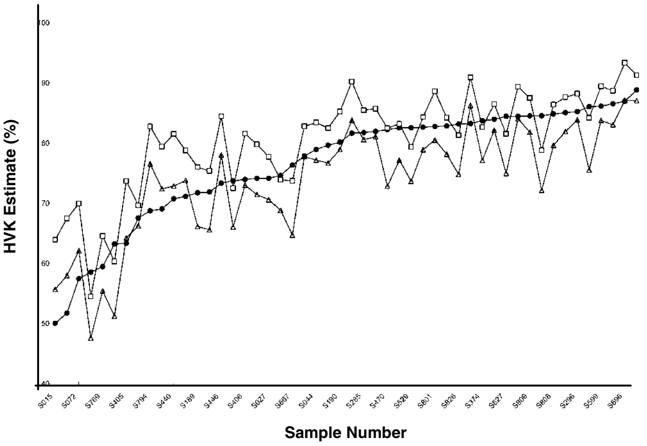

Fig. 4. Comparison of V-HVK scores (●) in export cargo samples with MV-HVK scores using original vitreous, piebald, and starchy classifiers (Δ), and using a two-step classifier with piebald kernel classification. The low-piebald category has been added to the vitreous category (□) to increase HVK score.

Subclassification of Piebald Kernels by Machine Vision

The classification of visually vitreous kernels into the piebald category by MV-HVK (Table III) was the classification category with the largest difference between the two HVK determination methods. The MV-HVK system was sensitive to small internal starchy spots that, in many cases, were not evident on the kernel surface. This was verified by cutting open such kernels. It was possible that the detection of these internal starchy spots was a primary cause of the large differences in total HVK scores between the two methods. Upon retesting of samples, a low number of piebald kernels were classified as vitreous (Table IV). To identify those kernels that were on the piebald-vitreous classification boundary, a second classifier was added to the MV-HVK system that separated the MV-HVK classified piebald kernels into three categories, low-piebald (≈<10% starchy endosperm), medium-piebald (≈>10% to <75% starchy endosperm), and high-piebald (≈>75% starchy endosperm). It was hypothesized that kernels that previously were close to the vitreous-piebald classification boundary would now be classified into the low-piebald bin, and that these kernels were the principle cause for MV-HVK scores being lower than V-HVK determinations. By adding the low-piebald fraction to the vitreous fraction, HVK scores were increased (Fig. 3). Unfortunately, this increased the HVK scores of all the samples to the same degree and did not significantly improve the agreement between V-HVK and MV-HVK as hypothesized. Similarly, adding the medium-piebald fraction to the combined vitreous and low-piebald components only increased MV-HVK scores but did not improve agreement between V-HVK and MV-HVK scores (data not shown). Therefore, the largest misclassification of vitreous kernels as piebald would appear to come from broken kernels as previously shown.

Sample Size

Another possible cause of error in the MV-HVK system was sample size. Generally, CV values dropped as HVK scores rose to >60% (Table VI). While the error term decreased for the 50 kernel samples when the number of replicates was increased from 5 (250 kernels) to 10 (500 kernels), the MV-HVK scores were not changed. The maximum noted change of 1.7% in HVK is of little practical significance in grading. No further significant decrease was found in the CV by increasing the sample size to 20 (1,000 kernels) (not shown). It is interesting to note that 10 samples of 50 seeds (500 kernels) equates to a sample size of ≈20 g, which lies between the 15-g domestic sample size and 25-g export sample size specified for V-HVK in Canadian grain grading (CGC 2001).

Testing MV- HVK Using Blended Railcar Lot Samples

Railcar lots of grain arriving at port locations have variable characteristics attributable to environment and genotype. Figure 1 has already shown that despite the variable characteristics expected in railcar lots, both MV-HVK and V-HVK are in reasonable agreement. To determine the effect of blending samples on MV-HVK determination, samples of railcar lots unloading at Thunder Bay terminal elevators were blended to produce durum samples with weighted HVK scores at 10% intervals. MV-HVK gave highly reproducible HVK score estimates that were in close agreement with V-HVK scores (Table VII). The blending of samples with similar HVK scores reduces the impact of environment and cultivar on classification.

Comparison of MV-HVK of Export Cargos to CGC Visual Procedure

Using machine vision, Sapirstein and Kohler (1995) previously established that export cargo samples of Canadian grain show greater uniformity than the railcar samples arriving at terminal locations. This is due to blending and cleaning operations in the terminals. In the current study, MV-HVK scores for cargo samples were in good agreement with V-HVK. Both initial and modified MV-HVK scores were used for comparison to V-HVK (Fig. 4). The original classifier tended to slightly underestimate the higher HVK scores as had previously been found, while the classifier where the low-piebald score was added to the vitreous score increased the MV-HVK score but did not significantly affect the relationship between MV-HVK and V-HVK.

CONCLUSIONS

Machine vision HVK scores are highly reliable and repeatable for Canadian export cargo samples of durum wheat where the influence of environment and cultivar are minimized due to blending. There is good agreement between MV-HVK and visually determination (V-HVK). For railcar samples of high grade, MV-HVK scores are also reliable and comparable to V-HVK scores. With lower grades, where other grading factors often predominate, agreement between MV-HVK and V-HVK is less robust. Known grading factors that affect MV-HVK are weathered, broken, and thin kernels. MV-HVK scores are repeatable in this situation, whereas the V-HVK scores can vary. V-HVK is a subjective assessment that operationally quickly determines HVK scores at railcar unload to facilitate binning decisions based on grade. The question arises whether MV-HVK should duplicate the V-HVK score, measure its own HVK score, or focus on predicting milling potential. Currently, durum wheat is traded using V-HVK as a value basis. The primary focus of research remains to characterize additional grading factors that affect the HVK kernel classification model and move the MV-HVK determination closer to the current system in use. In comparison to V-HVK, MV-HVK has the potential to predict the milling potential of a sample by enhanced kernel characterization through subclassification of piebald kernels and to determine other grading factors that influence end-product quality. This remains a future research option.

MV-HVK is a fast and repeatable procedure that could be used to segregate top grades of durum wheat of diverse origin. The model proposed here would be expected to function equally well with samples from outside Canada due to the imaging approach taken, although this has yet to be tried.

LITERATURE CITED

Black, H. C. 1966. Laboratory purifier for durum semolina. Cereal Sci. Today 11:533-534, 542.

Bolling, H., and Zwingelberg, H. 1972. Glasigkeit und Griessausberte bei Durumweizen. Getreide Mehl Brot 26:264-269.

CGC. 2001. Hard vitreous kernels. Pages 4-14 to 4-15 in: Official Grain Grading Guide. www.grainscanada.gc.ca. Industry Services, Canadian Grain Commission: Winnipeg, MB.

Dexter, J. E., and Edwards, N. M. 1998. The implications of frequently encountered grading factors on the processing quality of durum wheat. AOM Bull. October: 7165-7171.

Dexter, J. E., and Matsuo, R. R. 1981. Effect of starchy kernels, immaturity and shrunken kernels on durum wheat quality. Cereal Chem. 58:395-400

Dexter, J. E., Williams, P. C., Edwards, N. M., and Martin, D. G. 1988. The relationships between durum wheat vitreousness, kernel hardness and processing quality. J. Cereal Sci. 7:169-181.

Dexter, J. E., Marchylo, B. A., MacGregor, A. W., and Tkachuk, R. 1989. The structure and protein composition of vitreous, piebald and starchy durum wheat kernels. J. Cereal Sci. 10:19-32.

Dexter, J. E., Matsuo, R. R., and Kruger, J. E. 1990. The spaghetti-making quality of commercial durum wheat samples with variable α-amylase activity. Cereal Chem. 67:405-412.

Feillet, P., and Dexter, J. E. 1996. Quality requirements of durum wheat for semolina milling and pasta production. Pages 95-131 in: Pasta and Noodle Technology. J. Kruger, R. R Matsuo, and J. W. Dick, eds. Am. Assoc. Cereal Chem.: St. Paul, MN.

ICC. 1995. Standard Methods of the International Association for Cereal Science and Technology. Standard No. 129. Method for the determination of vitreousness in durum wheat. ICC: Vienna.

ISO. 1980. International Organization for Standardization. International

Standard 5532. Durum wheat—Determination of proportion of non-wholly vitreous grains (reference method). ISO: Geneva.

Matsuo, R. R., and Dexter, J. E. 1980. Relationship between some durum wheat physical characteristics and semolina milling properties. Can. J. Plant Sci. 60:49-53.

Matweef, W. 1963. Le mitadinage des blés durs, son évaluation et son influence le rendement et la valeur des semoules. Bull. Anciens Elèves Ecole Franc. Meunerie No. 198:299-306.

Menger, A. 1971. Probleme der Glasigkeit von Durumweizen. Getreide Mehl Brot 21:91-95.

Sissons, M. J., Osborne, B. G., Hare, R. A., Sissons, S. A., and Jackson, R. 2000. Application of the single-kernel characterization system to durum wheat testing and quality prediction. Cereal Chem. 77:4-40.

Sapirstein, H. D., and Bushuk, W. 1989. Quantitative determination of foreign material and vitreosity in wheat by digital image analysis. Pages 453-474 in: Proc. ICC 89 Symposium. Wheat End-Use Properties. H. Salovaara, ed. ICC: Vienna.

Sapirstein, H. D., and Kohler, J. M. 1995. Physical uniformity of graded railcar and vessel shipments of Canadian Western Red Spring Wheat determined by digital image analysis. Can. J. Plant Sci. 75:363-369.

Shatadal, P., Symons, S. J., and Dexter, J. E. 1988. Detecting hard vitreous kernels in durum wheat using image histogram. Paper No. 986028. ASAE: St. Joseph, MI.

[Received May 22, 2002. Accepted December 3, 2002.]