Achievements and Prospects of Wheat Breeding for Disease Resistance

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Abstract: Achievements and prospects of wheat breeding for disease resistance in the world and in the Czech Republic are reviewed. Attention is paid to rusts, powdery mildew, leaf blotch, glume blotch, tan spot, fusarium head blight, common and dwarf bunt, eyespot, barley yellow dwarf virus on wheat and wheat dwarf virus. Genes for resistance to rusts and powdery mildew in the cultivars registered in the Czech Republic are listed. Promising resistance genes and sources of resistance to the above mentioned diseases are reviewed. Prospects of resistance breeding including application of methods of molecular genetics and development of synthetic hexaploids are outlined.

Keywords: wheat; resistance breeding; fungal diseases; virus diseases; Czech Republic

The development of disease resistance breeding is closely linked with the development of genetics, plant pathology and the progress of plant breeding methods. First crosses of wheat based on Mendels genetic principles, aiming to transfer disease resistance, were carried out by BIFFEN (1905). He found monogenic inheritance of yellow rust resistance in wheat. Such inheritance has been later confirmed in other crops and pathogens. The discovery of physiologic races in cereal rusts (STAKMAN 1914) enabled exact genetic analyses of resistance. Studies on sources of resistance, particularly of wild relatives of crops, were performed by VAVILOV (1919, 1935) who also described geographic centres of origin of cultivated plants and resistance sources. Besides studies of inheritance of resistance, also the genetics of virulence was studied, which was often found monogenic (FLOR 1942). From his results on genetics of resistance in flax and virulence in flax rust FLOR (1956) developed the gene for gene hypothesis. PERSON (1959) demonstrated practical applications of this hypothesis, e.g. for the postulation of resistance genes using pathogen races with known virulence. Polygenic resistance became more popular when VANDERPLANK (1963) published his analysis and conclusions on vertical and horizontal resistance. Durability of disease resistance (defined by JOHNSON [1981]) attracted attention particularly in the last decade when several conferences were devoted to this aspect of resistance. Finally, recent development of molecular biology opened many new prospects for the resistance breeding.

SOURCES OF RESISTANCE

In the USA breeding for stem rust resistance in wheat was practised already in the first decades of the last century, when crosses with resistant bread wheat accessions were made. Apart of the use of resistance sources from bread wheat, the first interspecific crosses were carried out also in the USA. Of historical as well as of practical importance are the crosses: Jumillo (*Triticum durum*) × Marquis (*Triticum aestivum*), from which cv. Marquillo has been developed, and Yaroslav Emmer (*Triticum dicoccum*) × Marquis, from which the cvs Hope and H 44-24 were derived. The American rust resistance breeding had an impact on the breeding in Europe. E.g., in Austria the plant breeder Dr. LASSER (1951) used the cultivar Thatcher, whose rust resistant parent was Marquillo, to develop the cultivar Admonter Früh. Besides the gene *Sr5* from Thatcher also the gene *Sr2* from the

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cultivar Hope was widely used in wheat breeding. A translocation from *Thinopyrum ponticum* (*Agropyrum elongatum)* with the leaf rust resistance gene *Lr19*, that was developed also in the USA, was transferred into the Swedish cultivar Sunnan. The same translocation was used in Slovakia where the advanced line SO 997 (Lutea) was bred. In Europe, the work carried out in Germany at Salzmünde and Weihenstephan was of particular importance. The substitution 1B.1R and the translocation T1BL.1RS, developed there, possessed the linked resistance genes *Lr26*, *Yr9*, *Sr31* and *Pm8* from rye (BARTOŠ & BAREŠ 1971). Other translocations important for European wheat breeding were those from *Triticum ventricosum* (*Aegilops ventricosa).* E.g., the line VPM1 (from a cross of *Aegilops ventricosa, Triticum persicum* and cv. Marne) contains the gene *Pch2* conditioning eye-spot resistance. The line VPM1 was developed in France and its eye-spot resistance was transferred e.g., to the cvs Roazon and Rendezvous.The line VPM1 was developed in France and its eye-spot resistance was transferred e.g., to the cvs Roazon and Rendezvous. Resistance to rusts (linked genes *Yr17*, *Lr37* and *Sr38*) originates from the same source. Of the cultivars registered in the Czech Republic the cvs Apache and Corsaire possess that translocation with rust resistance genes. Several important genes for powdery mildew resistance were also transferred from alien species: e.g. *Pm2* from *Aegilops squarrosa* and *Pm6* from *Triticum timopheevi.* Both genes are present in many European cultivars, including Czech cultivars.

The above mentioned examples show the important role of interspecific or intergeneric crosses for resistance breeding of wheat. However, only a small part of the accomplished translocations has been transferred to commercial cultivars.

Mutation breeding was more important for barley (the gene *mlo*) than for wheat. In wheat, mutations were used successfully for obtaining translocations. The importance of somaclonal variation as a source of novel resistance remains limited. Progress in genetic engineering and genetic transformation opens new possibilities of resistance breeding in cereals (KUČERA *et al.* 2000).

WHEAT BREEDING FOR DISEASE RESISTANCE

MCINTOSH (1998) listed 23 fungal diseases, 5 virus diseases and 4 bacterial diseases of wheat and stated, that sources of resistance are available to all the diseases except two. However, the importance of single diseases varies with climatic conditions and crop management, e.g., application of fertilisers (particularly nitrogen), reduced or no tillage, etc. Breeding itself can also change the importance of diseases – those that were defeated by resistance breeding are superseded by other diseases.

Rust diseases

Stem rust (*Puccinia graminis* Pers.: Pers.)

Breeding for stem rust resistance was motivated by epidemics of this disease in North America. In Europe stem rust on wheat lost its importance in the last decades. This was probably due to successful resistance breeding in the countries of south-eastern Europe, from where airborne inoculum has usually spread to Central Europe. The last stem rust epidemic in Czechoslovakia and in south-east Europe was recorded in 1972. Though there is no immediate threat of stem rust, several cultivars registered in Czechoslovakia and in the Czech Republic have stem rust resistance based on the genes *Sr31, Sr11, Sr29*, *Sr37* and *SrTmp*. Older Czechoslovak wheat cultivars typically carried the gene *Sr5*, derived from eastern European cultivars (BARTOŠ *et al.* 1970). The genes *Sr2* and *Sr36* played an important role in American breeding. *Sr36* was also used in Hungarian wheat breeding (e.g. cv. Kincső) (VIDA *et al.* 2000).

Yellow rust (*Puccinia striiformis* Westend)

Yellow rust is an important disease particularly in western Europe, where novel races often threaten the so far used resistances. Recently virulence to *Yr17*, an as yet important gene in western European cultivars, is spreading. The resistance of some cultivars, e.g. of Cappelle Desprez, is more durable. Field resistance has been found to be considerably durable and effective, e.g. in the cv. Alcedo (MEINEL 1997). In Czechoslovakia and later in the Czech Republic, yellow rust resistance was obligatory for all cultivars on the official variety list since the sixties. This substantially helped to avoid losses caused by yellow rust till recently. The only exception was a short period when the Yugoslav susceptible cultivars Sava and Zlatna Dolina were grown because of lack of very early wheats. In the last years also yellow rust susceptible cultivars were registered and for this reason yellow rust finds its hosts again easier. This contributes to a new wave of yellow rust. Since 1999 the disease is occurring more frequently also in other eastern European countries.

Leaf rust (*Puccinia persistens* Plow. subsp. *triticina* [Eriks.] Urban et Marková = *Puccinia recondita* Rob. ex Desm. f.sp. *tritici*)

Leaf rust is causing losses particularly in warm dry summers. Its economic importance is increasing. Resistance breeding in the world was particularly successful when partial, field or adult plant resistance was exploited. An example is the gene *Lr34* in the CIMMYT wheat breeding, linked with *Yr18*, *Byd1* and *Ltn*. Leaf tip necrosis can be utilised as a marker for *Lr34*. The modern strategy of resistance breeding described by WINZELER (1995) combines greenhouse and field tests. Recent ring tests organised by WINZELER *et al.* (2000), rust race surveys (MESTERHÁZY *et al*. 2000; BARTOŠ *et al*. 2001) and analyses of *Lr* genes in cultivars grown in the U.K. (SINGH *et al*. 2001) and in France (GOYEAU & PARK 1997) contributed to the knowledge of types of leaf rust resistance and resistance genes in cultivars grown in Europe. Adult plant resistance was found e.g., in the cvs Batis, Capo, Josef and Bontaris; adult or partial resistance in the cvs Lindos, Runal, Compass and Caxton. All these cultivars have the *Lr13* gene for adult plant resistance, but differ in the degree of field resistance (WINZELER *et al*. 2000). In European cultivars the following genes for leaf rust resistance were postulated: *Lr1*, *Lr3a*, *Lr3ka*, *Lr10*, *Lr13*, *Lr14a*, *Lr17b*, *Lr20*, *Lr26* and *Lr37* (WINZELER *et al*. 2000; SINGH *et al*. 2001). Almost all of them were also postulated in cultivars registered in the Czech Republic, namely *Lr1*, *Lr3a*, *Lr3ka*, *Lr10*, *Lr13*, *Lr14a*, *Lr17b*, *Lr26* and *Lr37*. Unfortunately, these genes are only partially effective or ineffective against the prevailing races. Czech cultivars were fairly well protected by *Lr1* (cv. Vlada) or the combination of *Lr10* and *Lr13* (cvs Siria and Alka). Recently their resistance declined. The important field resistance of cv. Viginta was used in the breeding of many Czech and Slovak cultivars (e.g., Astella, Barbara, Blava, Boka, Bruneta, Klea, Samanta, Saskia, Solara and Solida). However, only some of these cultivars are similarly resistant to leaf rust as Viginta. In eastern European cultivars, that were frequently used in the Czechoslovak wheat breeding, the gene *Lr3* was common (BARTOŠ *et al*. 1969). In recent international race surveys the genes *Lr9*, *Lr19* and *Lr24* were highly effective against leaf rust (MESTERHÁZY *et al*. 2000).

In Czechoslovakia race surveys of rusts on wheat started in the sixties. Results obtained till 1995 have been analyzed by BARTOŠ *et al*. (1996).

The survey of rust and powdery mildew resistance genes in winter wheat cultivars registered in the Czech Republic is given in Table 1.

Powdery mildew (*Blumeria graminis* [DC.] Speer = *Erysiphe graminis* de Candolle)

The resistance genes *Pm2, Pm6, Pm4b, Pm8* and *Pm5* occur often in European wheats, including Czech cultivars (Table 1). Their importance is limited, since they are ineffective against most of the recent powdery mildew races. The gene *Pm8* becomes ineffective in presence of the suppressor gene *SuPm8* (HANUŠOVÁ 1992; HANUŠOVÁ *et al*. 1996; ZELLER & HSAM 1996; REN *et al*. 1996). Partial or field resistance to such a variable pathogen as powdery mildew is of great importance. It has been described e.g., in the cv. Mironovskaya 808, from which the German cultivars Miras and Mikon were derived. Among Czech cultivars the best powdery mildew resistance was registered in the cv. Vlasta from the cross Brimstone/Š13//Hana (ŠÍP *et al*. 1999). The powdery mildew resistance of Š13 is derived from *Triticum monococcum* and the responsible gene was designated *Pm1b* (ZELLER & HSAM 1998). However, in the cv. Vlasta the genes *Pm2* and *Pm6* were postulated (obviously derived from Brimstone) but *Pm1b* has not been found (Zeller – pers. com.). Further study is going on because a mere presence of *Pm2* and *Pm6* cannot explain the high resistance of cv. Vlasta in the field, in comparison with other cultivars with *Pm2* and *Pm6*.

Reviews on wheat powdery mildew resistance genes and their use in breeding were published by SZUNICS and SZUNICS (1999) and by CHEN and CHELKOWSKI (1999).

Leaf blotch (*Mycosphaerella graminicola* [Fuckel] Schröter, anamorph *Septoria tritici* Rob. ex Desm.)

The economic importance of leaf blotch is increasing worldwide, as was demonstrated at the CIMMYT workshop in Mexico (VAN GINKEL *et al*. 1999). Results of several genetic studies indicate, that resistance is conditioned oligogenic. Major as well as minor genes governing resistance have been described. Four *Stb* resistance genes for leaf blotch resistance have been registered (MCINTOSH *et al*. 1998). In the CIMMYT breeding program three main groups of resistance sources were successfully used: (a) Russian winter wheat lines, (b) lines from the Southern Cone of South America and (c) to lesser extent also lines from the USA (GILCHRIST *et al*. 1999). Resistance to leaf blotch is present in the cvs Bezostaya 1, Anza, Bobwhite and in the synthetic hexaploid lines from the cross *Triticum durum* × *Triticum tauschii* (VAN GINKEL & RAJARAM 1999). In field trials in the Netherlands, Switzerland and the U.K. between 1995 and 1997 (BROWN *et al*. 2001) the Brazilian cultivar Veranopolis, a well-known source of resistance (ROSIELLE 1972), was the most resistant entry. The breeding programme at FAP/FAL (Switzerland) has been notably successful in developing wheat with good resistance to septoria tritici leaf blotch, as indicated by low scores for Arina and five Swiss breeding lines in the experiments of BROWN *et al*. (2001).

Resistance has been often found associated with plant height and late maturity. Genotypes with *Rht2* seemed to be more resistant than those with *Rht1*. Specific interactions between certain cultivars and isolates of the pathogen have been confirmed (KEMA *et al*. 1996a, b; BROWN *et al*. 1999, 2001). Changes in the pathogen population caused "loss of resistance" of the cv. Gene (MUNDT *et al*. 1999). Successful breeding for durable resistance must take into account specific host-pathogen interactions to avoid the breakdown of host resistance by specifically virulent isolates. Accumulation of different resistant genes in a genotype appears to be an important prerequisite of success in the breeding for resistance. BROWN *et al*. (2001) suggest that progress

Table 1. Rust and powdery mildew resistance genes in winter wheat cultivars registered in the Czech Republic (genes *Lr3ka, Lr13, Lr14a* and *Lr17b* postulated by R.F. Park)

Cultivar	Registered	Origin	Resistance genes			
			Lr	*Sr*	*Yr*	*Pm*
Košútka	1981	SK	+	+	+	–
Regina	1982	CZ	–	–	1, 2, HeIV	5, *SuPm*8
Viginta	1984	CZ	3	5, ++	2, 3a, 4a	–
Hana	1985	CZ	3	29	2	–
Sparta	1988	CZ	3, 26	31	9	2, 4b, 8
Ilona	1989	SK	–	11		5
Sofia	1990	CZ	3, 26	31	9	2, 4b, 8
Vlada	1990	CZ	1, 3, 13	+, +, +	+	5
Livia	1991	SK	13, 26	11, 31	9	8
Simona	1991	CZ	–	+		–
Blava	1992	SK	3ka	+	+	–
Torysa	1992	SK	+	29		2.6
Vega	1992	CZ	3	+	2	–
Samanta	1993	CZ	3, 13	+		–
Sida	1993	CZ	26	31	9	4b, 8
Asta	1994	CZ	3a, 13	+	1	2.6
Bruta	1994	CZ	13, 14a	+		–
Mona	1994	CZ	3, 13, 26	31	9	8
Rexia	1994	SK	3	+	3a, 4a	–
Siria	1994	CZ	10, 13	–	3a, 4a	4b, 6, *SuPm*8
Trane	1994	DE	26	31	9	8
Alka	1995	CZ	10, 13	+		+
Astella	1995	SK	3	–		–
Boka	1995	CZ	–	5?	3a, 4a	–
Estica	1995	NL	13, 14a	–		2.6
Ina	1995	CZ	–	5?	1	–
Samara	1995	CZ	13	–	1	2.6
Athlet	1996	DE	26	31	9	2.8
Brea	1996	CZ	3	+		–
Bruneta	1996	CZ	3	+		–
Ritmo	1996	NL	13	–		2.6
Saskia	1996	CZ	3	+		–
Alana	1997	CZ	+	+		
Ebi	1997	DE	–	–		
Šárka	1997	CZ	+	+		
Versailles	1997	NL	–	–		2.6
Contra	1998	DE	13, 17b	–		2, 6, 4b, 5
Elpa	1998	DE	+	–		6
Nela	1998	CZ	–	–		
Solara	1998	SK	+	+		
Apache	1999	DE	37	38	17	
Corsaire	1999	DE	37	38	17	2, 6, 4b
Niagara	1999	CZ	3	11		
Record	1999	DE	–	–		2, 6, 4b
Rialto	1999	UK	10, 13, 26	31	9	8
Semper	1999	NL	3			
Sepstra	1999	DE	+			
Vlasta	1999	CZ	+	–		2, 6, +

+ undetermined gene(s); – no gene found, blank means not tested

Table 2. Average response (1997–2000) of winter wheat cultivars (lines) that showed a higher (SDP < 3) resistance to infection with *Septoria tritici* in comparison with the susceptible cv. Galaxie

Cultivar	SDP	ILA
Arina	0.83	0.75
CH 76 106	0.75	1
Apollo	0.75	1
NSL 92-5719	0.75	0.5
SG-S 148-97*	1.75	1.88
Sida	1.75	1.42
Hereward	1.17	1.58
Ina	2.33	1.42
Ritmo	2.42	1.75
Versailles	2.75	2.17
Athlet	2.75	2.67
Samara	2.91	2.17
Galaxie	6.5	5.25
Total average of 26 cultivars	3.89	2.96

SDP = Septoria disease progress (0–9; 9 = the highest rate of disease spreading)
ILA = Infected leaf area (0 = 0%; 1 = 10%; 2 = 20% etc)
*line tested only 1998–1999

in improving resistance to septoria tritici leaf blotch may be achieved by intercrossing lines from different European breeding programmes.

In the Research Institute of Crop Production (RICP) Prague-Ruzyně the response of selected winter wheat cultivars to artificial infection with *Septoria tritici* has been studied since 1997. The results were summarised recently by Šíp *et al*. (2001). High resistance was found in the cv. Arina that was also resistant to *Fusarium* head blight. From Czech cultivars or lines SG-S 148-97, Sida, Ina and Samara showed a fairly good resistance (Table 2). In the experiments of Brown *et al*. (2001) high resistance was detected in the lines SG-RU-5007 and RU-5-96, developed in RICP Prague-Ruzyně. These lines were similarly classified also by Šíp *et al*. (1997).

Glume blotch (*Phaeosphaeria nodorum* [E. Müller] Hedjaroude, anamorph *Stagonospora nodorum* [Berk.] Cast. & Germ. = *Septoria nodorum* [Berk.] Berk.)

Glume blotch remains an important disease particularly at higher altitudes with frequent rainfalls. The genetic background of resistance of leaves differs from that one of ears. Again another genetic mechanism governs disease tolerance. Differences between reactions of seedlings and adult plants have been also observed. Resistance sources have been described, e.g., the cvs Atlas 66, Blueboy II, Frondoso, Fronthatch and Oasis (van Ginkel & Rajaram 1999). Sources of resistance to leaf blotch and glume blotch are usually not identical. Four *Snb* resistance genes for glume blotch (one with provisional designation) have been described (McIntosh *et al*. 1998).

In field inoculation experiments, carried out at the RICP Prague-Ruzyně for three years, a fair level of resistance has been found in the cvs Senta, Siria, Regina and Simona (Table 3). Cv. Mironovskaya 808 showed the lowest average septoria-caused reduction of TKW (thousand kernel weight). Several cultivars displayed a high disease severity but only a low decrease in TKW, e.g., Košútka, Vega and Danubia.

Difficulties in the breeding for resistance to leaf- and glume blotch have been defined by van Ginkel and Rajaram (1999) as follows:
1. earliness affects the expression of resistance,
2. correlation between seedling and adult plant resistance is variable,
3. correlation between symptoms and yield depression is also variable,
4. different Septoria isolates can influence each other on the leaf surface,
5. importance of pathogen races for resistance breeding has still to be clarified.

Tan spot (*Pyrenophora tritici-repentis* [Died.] Drechs., anamorph *Drechslera tritici-repentis* [Died.] Shoem. = *Helminthosporium tritici-repentis* [Died.] Died.)

Economic importance of tan spot is increasing worldwide. In the neighbouring Bavaria the disease was studied already 15 years ago Obst (1988). An international conference on this topic took place at Winnipeg, Canada, in 1998. Contributions from the conference have been summarised in the Canadian Journal of Plant Pathology in 1998. Tan spot was in 1997 also the topic of a CIMMYT workshop at El Batan, Mexico (Duveiller *et al*. 1998). *Pyrenophora tritici-repentis* develops races that differ by specific toxins (PtrTox A, B, C) and symptoms (chloroses or necroses) on particular wheat cultivars (differentials). A susceptible reaction appears when the pathogen produces a toxin for which the host has the corresponding receptor. Inheritance of resistance has been described as qualitative and mostly recessive. However, quantitative resistance has been also observed. As sources of resistance can be utilised the cvs Frontana, Bluebird, Kavkaz and lines derived from *Agropyron distichum* (Riede *et al*. 1996).

The response of 23 winter wheat cultivars to artificial infection with *Pyrenophora tritici-repentis* has been tested under field conditions at the RICP Prague-Ruzyně since 1999. Most cultivars registered in the Czech Republic were included in the tests. The three year study

Table 3. Comparison between average leaf and ear infestation with *Stagonospora nodorum* (symptom scoring on a 0–9 scale; 9 = highly infested) and average reduction of thousand kernel weight (TKW) (field experiments lasting three years 1993–1995)

Cultivar	Symptom score (0–9)	Cultivar	Reduction of TKW (%)
Senta	2.4	Mironovskaya 808	10.4
Siria	2.4	Regina	11.7
Regina	2.5	Senta	12.0
Simona	2.5	Siria	13.4
Mironovskaya 808	3.1	Zdar	14.0
Sofia	3.1	Simona	14.2
Torysa	3.1	Asta	16.2
Hana	3.3	Samara	16.7
Zdar	3.5	Hana	17.2
Asta	3.7	Danubia	19.8
Samara	3.7	Sofia	21.4
Ilona	4.3	Vega	21.7
Vlada	4.7	Košútka	22.2
Iris	4.8	Torysa	23.9
Bruta	5.1	Blava	24.5
Sida	5.1	Vlada	24.8
Sparta	5.1	Sida	25.2
Branka	5.2	Branka	25.8
Blava	5.3	Barbara	25.9
Košútka	5.3	Iris	26.0
Vega	5.3	Bruta	27.1
Danubia	5.4	Ilona	28.5
Barbara	5.5	Livia	29.5
Livia	5.5	Boka	30.0
Boka	5.5	Samanta	30.9
Viginta	5.9	Sparta	31.5
Samanta	6.0	Viginta	31.5

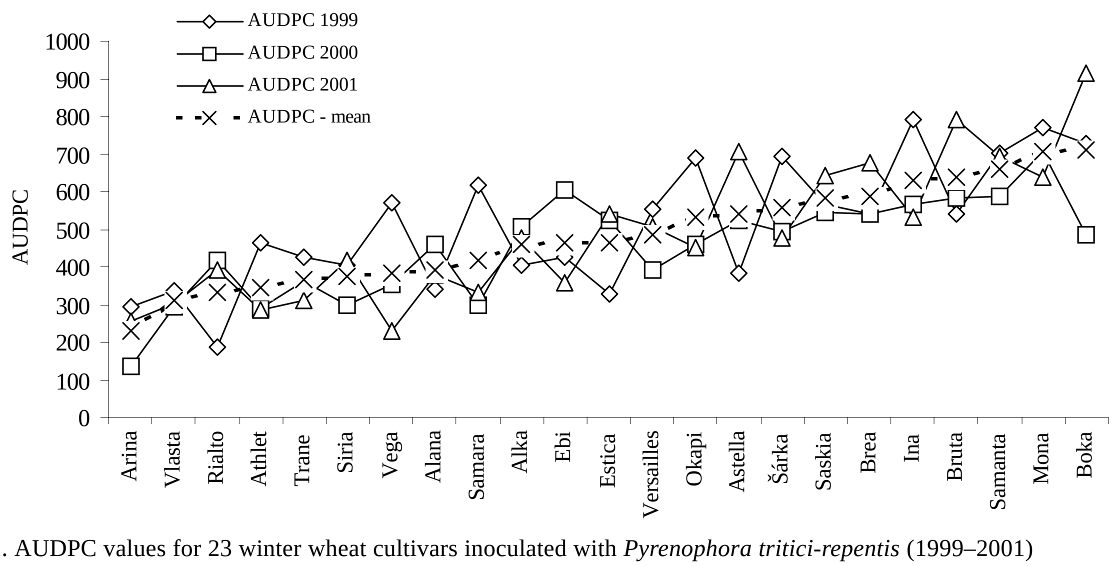

Fig. 1. AUDPC values for 23 winter wheat cultivars inoculated with *Pyrenophora tritici-repentis* (1999–2001)

revealed distinet differences between the cultivars, as can be seen from Fig. 1. The later maturing cultivars were more resistant to artificial infection than earlier maturing cultivars. AUDPC values of the cultivars Arina, Vlasta, Rialto, Athlet, Trane, Siria, Vega, Alana, Samara were significantly lower than of the susceptible cultivars Samanta, Mona and Boka (Table 4).

Table 4. Average response (1999–2001) of 23 winter wheat cultivars to artificial infection with *Pyrenophora tritici-repentis* -cultivar ranking and their inclusion into homogeneous groups (Duncan $P = 95\%$)

Cultivar	Average AUDPC	Homogeneous group
Arina	228.2	a
Vlasta	311.0	ab
Rialto	331.7	abc
Athlet	346.4	abc
Trane	365.9	abcd
Siria	374.3	abcd
Vega	383.3	abcd
Alana	393.3	abcd
Samara	416.3	abcde
Alka	461.3	bcdef
Ebi	462.6	bcdef
Estica	463.7	bcdef
Versailles	483.7	bcdef
Okapi	532.1	bcdefg
Astella	538.6	cdefg
Šárka	555.4	cdefg
Saskia	583.4	defg
Brea	587.1	defg
Ina	630.2	efg
Bruta	637.6	efg
Samanta	660.1	fg
Mona	704.8	g
Boka	710.1	g

Fusarium head blight (FHB) (*Fusarium* spp.)

Head blight, caused by various *Fusarium* species (in our country mainly by *Fusarium culmorum* [W. G. Smith] Sacc. and *Fusarium graminearum* Schwabe), attracts worldwide much attention mainly because of the toxins produced by the pathogen (MESTERHÁZY 1995) Several mechanisms of resistance are possible, namely:
1. resistance to invasion,
2. resistance to spreading,
3. resistance to toxin accumulation,
4. resistance to kernel infection,
5. tolerance.

All genetic studies deal so far with resistance type 2. There is no information on the genetic background of the other four types (MESTERHÁZY *et al*. 1999).

Earlier recommended separate tests with several isolates of the pathogen can be simplified. According to MESTERHÁZY (2001) application of one highly pathogenic isolate of *Fusarium graminearum* or *Fusarium culmorum* seems to be sufficient for the selection of resistance. This is very important, since parallel breeding against different *Fusarium* species then appears unnecessary.

Most of the popular sources of resistance, Nobeoka Bozu, Sumai 3 and Beijing 8, are, unfortunately, wheats of low agronomic value. Their utilisation requires, therefore, extensive prebreeding to improve the agronomic traits. However, advanced breeding lines with good agronomic performance, obtained after hybridisation with the above mentioned sources, are now available, e.g., from the Hungarian 'Szeged' breeding programme (MESTERHÁZY 2001). Another possibility of obtaining satisfactory resistance is to combine moderately resistant cultivars in hybridisation programmes.

In the RICP Prague-Ruzyně field inoculation experiments are performed each year since 1992. The response of different winter wheat cultivars (mainly cultivars registered in the Czech Republic and advanced breeding lines) to artificial infection with a highly pathogenic isolate of *Fusarium culmorum* is described in detail by STUCHLÍKOVÁ and ŠÍP (1996) and ŠÍP and STUCHLÍKOVÁ (2000). The detection of moderate resistance to the fusarium head blight in the advanced breeding lines SG-U-513 and SG-U-466 (Bona) from the cross Hana/Brock is of considerable practical importance. These lines can be readily used in wheat breeding, because they possess many other positive characteristics (ŠÍP & STUCHLÍKO-VÁ 1997). Cultivars and lines that showed a high resistance level (score L1) in tests in the last three (two) years are listed in Table 5.

Table 5. Symptom scores (on 0–4 scale) of winter wheat cultivars (lines) that showed a high level of resistance to infection with *Fusarium culmorum* in three (two) years in comparison with the susceptible cultivar But

Cultivar/line	1999	2000	2001	Average
Arina	1	0.8	0.4	0.73
Apache	1	0.6	0.8	0.8
Ebi	1	0.3	1.1	0.8
SG U 513	0.5	0.8	1.2	0.83
Tower	0.9	0.6	1.2	0.9
Alana	0.9	0.8	1.3	1
SG V NB × MN SUM3		0.1	0.1	0.1
SG-RU 24 (Rheia)		0.6	0.3	0.45
Ludwig		0.6	1.2	0.9
But	3.5	1.7	3.1	2.77
Average of all tested cultivars	2.01	1.24	2.17	1.81

Much attention has recently been paid to the relation between infection severity and accumulation of mycotoxins (especially deoxynivalenol – DON) in wheat grains. It is supposed that other factors than resistance influence strongly the DON contamination (MESTERHÁZY 2001). In our experiments DON content was highly influenced by years, locations and fungus isolates. Besides this, also isolates of different chemotypes (causing accumulation of specific mycotoxins in the cereal grain: DON, nivalenol, zearalenol etc.) have been identified (PERKOWSKI *et al*. 1997). However, in materials that were highly resistant to FHB no or very little accumulation of DON has been detected (MESTERHÁZY *et al*. 1999). Great variability in DON content usually occurred under susceptible conditions (LEMMENS *et al*. 1997). Anyhow, the relationship between the disease symptoms and DON content remains not yet well understood.

Common and dwarf bunt (*Tilletia caries* [DC.] Tul., *Tilletia laevis* Kühn, *Tilletia controversa* Kühn)

Though the time when common bunt belonged to the most important wheat diseases is over (at least in most parts of Europe), breeding for bunt resistance exists in many countries. Bunt resistance remained important in North America, Russia, the Ukraine, Romania, Bulgaria and Turkey. Also in Scandinavian countries breeding for bunt resistance continues and a project for international cooperation is being prepared. At least 25 *Bt* genes for bunt resistance have been described and genes in several sources of resistance remain to be determined and described. GOATES (1996) listed 30 races of *Tilletia caries,* 10 of *Tilletia laevis* and 17 of *Tilletia controversa.*

Sources of bunt resistance have been tested in the RICP Prague-Ruzyně (BLAŽKOVÁ & BARTOŠ 1997b) and the bunt resistant Swedish cultivars Tjelvar (T1BL.1RS) and Stava were selected for crossing with Czech cultivars (BLAŽKOVÁ & BARTOŠ 1997a). Resistant short straw lines, earlier than Tjelvar and with improved breadmaking quality, have been produced. The bunt resistance of Tjelvar is derived from PI 178383 with the resistance genes *Bt8*, *Bt9* and *Bt10*. This line is in North America an important source of resistance, both to common and dwarf bunt. The physiologic races T1, L3 and L5 have been identified in bunt samples from the Czech Republic. Bunt samples from ten other countries were also analysed. The most frequent races were L5/T5 and L3/T3, with virulence for the genes *Bt7*, *Bt2* and *Bt1* (BLAŽKOVÁ & BARTOŠ 2002).

Eyespot and other root and crown diseases

The main sources of resistance to eyespot (*Pseudocercosporella herpotrichoides* [Fron] Deighton) are the cv. Cappelle Desprez, the line VPM1 and cultivars derived from them. Four *Pch* genes have been described, one of them with a preliminary designation. Effective resistance sources to causal agents of other root diseases of wheat are not available (MCINTOSH 1998).

***Barley yellow dwarf virus* (BYDV)**

BYDV is transmitted by several species of aphids and causes the probably most important virus disease of cereals, which is spread worldwide on wheat, barley and other cereals. It is a luteovirus with several strains, of which the PAV strain prevails in the Czech Republic. Resistance is considered the only effective means of controlling the damage caused by this disease every year to cereals.

Resistance breeding was practised mainly within CIMMYT and ICARDA hybridisation programmes. A large collection of resistant spring wheat lines is now available to breeders worldwide. Tolerance to BYDV is in wheat mainly based on the *Bdv1* gene (SINGH *et al*. 1993), which could have originated from the Brazilian cultivar Frontana (parent of the cultivar Maringá) and should be considered a source of durable resistance, because of its long lasting effectiveness in spite of its presence in numerous CIMMYT wheats deployed worldwide. Great attention was also paid to interspecific or intergeneric hybrids (especially with wheatgrass *Thinopyrum intermedium* or *T. ponticum)* as new sources of BYDV resistance (AYALA *et al*. 2001). The amphiploid OK 7211542, derived from hybrids of wheat with *Thinopyrum ponticum,* was found to be immune to BYDV. According to CHEN *et al*. (1997), it has a great potential for transferring BYDV resistance into wheat.

In the RICP Prague-Ruzyně the materials obtained from CIMMYT and ICARDA programmes, together with advanced lines and registered spring and winter wheat cultivars were tested for resistance to the PAV strain of BYDV (ŠÍP *et al*. 1995; VACKE *et al*. 1996). In winter wheats only the cvs Sparta, Sofia, Danubia and the advanced line SG-U 2105 showed moderate resistance to BYDV. In spring wheat, however, valuable sources of resistance have been found, e.g., WKL-91-138, Maringá with *Rht1* and *Rht2*, or VEE"S"/TRAP1 (Table 6). These sources were crossed with the winter wheat cultivar Sparta. Resistant lines (symptom score¸ 3) were selected among the progenies (VACKE *et al*. 1996). Two advanced lines of spring wheat, SG-S-604/96 and SG-S- 26/98 from the Plant Breeding Station Stupice, SELGEN, a.s., showed in tests at RICP Prague-Ruzyně and CIMMYT, Mexico (M. Henry – pers. com.) a good resistance level (Table 6). Because these lines have many other positive characteristics (especially very high yielding ability and high resistance to yellow rust, leaf rust and powdery mildew), they are now widely used in hybridization programmes of the SELGEN company.

Table 6. Average values of yield characters and symptom scoring (0–9; 0 = without symptoms) after infection with BYDV in wheat cultivars (lines) that showed in 1997–2000 a higher resistance level (Jara and Vlada: susceptible checks)

Cultivar	Vegetation type	Grain yield (t/ha)	Grain weight per ear (g)	Symptom score
WKL-91-138	S	2.85	1.26	1.9
Maringá *Rht1+2*	S	3.77	1.08	2.2
Anza (*Bdv1* gene)	S	3.22	1.18	3.0
Maringá *Rht1*	S	3.83	1.29	3.9
Maringá *Rht2*	S	4.17	1.31	3.5
SG-S-26/98*	S	4.48	1.31	3.5
VEE"S"/TRAP 1	S	3.95	1.22	4.3
SG-S-604/96*	S	4.21	1.25	5.0
Jara	S	1.95	0.69	7.2
Sparta	W	4.14	1.28	4.8
Sofia	W	4.00	1.25	4.3
Danubia	W	3.87	1.29	4.9
SG-U 2105	W	4.58	1.41	4.7
Vlada	W	2.53	0.72	7.1

*confirmed by tests in CIMMYT Mexico; in RICP tested in 1999 and 2000
S = spring; W = winter

Wheat dwarf virus (WDV)

The WDV is a leafhopper (*Psammotettix alienus*) transmitted geminivirus, which was for the first time described on the territory of Czechoslovakia (VACKE 1961), later in other European countries. A WDV strain, adapted to barley and not transmissible to wheat, was identified much later in the early nineties. In the last years severe infections by WDV were recorded in both winter wheat and winter barley crops and resistance in wheat and barley cultivars became a very important goal.

About 200 wheat cultivars were tested for resistance to WDV in the RICP Prague-Ruzyně. High resistance levels have not been found (VACKE & CIBULKA 2000). Of the Czech and Slovak cultivars only Astella, Boka, Bruneta, Bruta, Ilona, Mona, Saskia and Senta, and of foreign cultivars Belocerkovskaya, Kharkovskaya, Mironovskaya 808, Yubileynaya and Kawvale showed a slight WDV-caused yield depression.

MOLECULAR TECHNIQUES IN RESISTANCE BREEDING

The number of molecular markers of resistance genes is rapidly growing. Also QTLs are extensively investigated. LANDRIDGE and CHALMERS (1998) published a list of markers of wheat resistance genes. It contained 21 markers for rust resistance genes, 7 markers for powdery mildew resistance genes and markers for resistance genes to virus diseases, common bunt, loose smut, eyespot and tan spot. In Sumai 3, an important source of head blight resistance, five QTL have been determined (ANDERSON *et al*. 1998). Marker assisted selection will be applied particularly in cases when resistance tests take too much time and are expensive (e.g., tests of resistance to virus diseases or bunt) or for pyramiding of resistance genes. Genes for antifungal proteins that condition resistance to *Fusarium* head blight have been transferred (FRY *et al*. 1998). Transfers of genes for chitinase, glucanase and ribosome inhibiting proteins, that enhance resistance, were carried out in CYMMIT, Mexico (FENNEL *et al*. 1998). To obtain transgenic wheat plants, particle bombardment appeared to be the most successful method. At present 420 applications for deliberate release of GMO into the environment are registered in the EU member states for maize, 3 applications for barley and 13 applications for wheat (KUČERA *et al*. 2000).

At the RICP Prague-Ruzyně microsatellite analysis was used for the identification of wheat cultivars. The detected alleles were numbered, catalogued and used further to produce an electronic profile of each cultivar (LEIŠOVÁ & OVESNÁ 2001). Polymorphic DNA profiles of wheat cultivars can be used, for example, to measure dissimilarity of cultivars, to monitor the genetic background of particular cultivars etc.The latter might help to accelerate backcross procedures and to transfer deliberately gene complexes. Molecular markers are especially useful for the development of new sources of resistance with the now available rust resistance genes. SCHACHERMAYR *et al*. (1997) used a molecular marker for the gene *Lr10*. With this marker *Lr10* has been identified in the Czech cvs Alka, Siria and several foreign cultivars (BLAŽKOVÁ *et al*. 2002).

PROSPECTS OF DISEASE RESISTANCE BREEDING IN WHEAT

Molecular genetics offers many new possibilities for the intensification of resistance breeding. However, the costs of these techniques are limiting their broad application. The progress in the development and application will depend on available funding and cooperation of universities and research institutes with wheat breeders. The concentration of plant breeding in big companies with global activities may support a fast development and broad application of molecular biology in wheat breeding. This can be demonstrated by the increasing number of available molecular markers of resistance genes. Not only the application of molecular techniques, but also conventional wheat breeding will become more expensive, because resistance to a larger number of diseases has to be considered. Costs of breeding may also increase because a free exchange of resistance sources will be probably restricted in the future.

There is growing interest in breeding for partial resistance. In CIMMYT 60% of breeding expenses is spent on breeding for partial resistance. RAJARAM (1999) from the same organization considered for the next years field selection to be still more important for the yield increase than any other methods. Interspecific and remote crosses will continue to play an important role in the future, together with direct transfer of resistance genes. However, partial resistance can be increased also by the accumulation of minor genes by intercrossing bread wheat lines or cultivars possessing already a certain level of this resistance. An important CIMMYT programme concentrates on the broadening of genetic diversity. Synthetic hexaploids are produced by crossing *Triticum durum* with *Triticum tauschii* (donor of the D genome). After several backcrosses lines possessing resistance to *Tilletia indica* or *Fusarium graminearum* have been selected. As a source of resistance to yellow- and leaf rust, powdery mildew and virus diseases *Triticum dicoccoides* was frequently used in the CIMMYT breeding programme (RAJARAM 1999). Another aim is to find a resistance gene in wheat or wheat relatives with characteristics similar to the *mlo* gene of barley.

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Abstrakt

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V práci jsou shrnuty výsledky a perspektivy šlechtění pšenice na odolnost k chorobám ve světě a v České republice. Pozornost je zaměřena na rzi, padlí travní, braničnatku pšeničnou, braničnatku plevovou, žlutou skvrnitost listů působenou houbou *Pyrenophora tritici-repentis*, fuzariózu klasu, sněť mazlavou a zakrslou, stéblolam, virus žluté zakrslosti ječmene na pšenici a na virovou zakrslost pšenice. Jsou uvedeny geny rezistence ke rzím a padlí travnímu v odrůdách pšenice registrovaných v České republice. Je podán přehled perspektivních genů a zdrojů rezistence k uvedeným chorobám. Jsou nastíněny perspektivy šlechtění pšenice na odolnost včetně aplikace metod molekulární genetiky a tvorby syntetických hexaploidů.

Klíčová slova: pšenice; šlechtění na rezistenci; mykózy; virózy; Česká republika

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