Glider Pilot Workload: Cardiopulmonary Regulation and Energy Expenditure

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1. Introduction

In glider flying, emotional, mental, and physical load factors are existent which differ markedly from "pilot workload" described for pilots of other types of aircraft [10]. Thus, aeromedical data available from the literature may not be assumed for glider pilots uncritically.

To evaluate pilot workload, time- and event-synchronous observation of pilot heart rate, heart rate variability or respiration rate were used by many authors [9, 19, 20, 28, 29, 30, 32, for detailled lit. see 12]. In glider pilots heart rate response on the stress of flying was evaluated by Burchardt [5], Clasing [6, 7], and Neubert [25]. Since the observation of heart rate or respiration rate alone (as integral parameters of emotional stress, as well as of physical activity) are not sufficient to separate physical and psychological factors in pilot workload, the measurement of various cardiac and pulmonary parameters needs to be included to permit this analysis. Spiroergometric methods permit measurement of oxygen uptake and energy expenditure, and allow to understand the cardiopulmonary regulation for a given workload [15, 16].

Here, oxygen uptake is considered to be the most appropriate physiological equivalent of pure physical work [15].

Using portable spirometric methods, 29 glider pilots were examined during short duration glider flights. The aims of this study were:

(1) to evaluate cardiopulmonary change and regulation during glider flights started either by winch tow or aerotow launching;

(2) to identify the relevance of individual aerobic capacity and flight experience on cardiopulmonary regulation in flight;

(3) to separate cardiopulmonary changes caused by psychological and by physical workload factors.

2. Methods

Twenty-nine male glider pilots, age range 16 to 42 years ($\bar{x}$ = 25,7 y), were examined. Twenty-four pilots started their flights with winch (*W*) and five with aerotow launching (*F*). The results for both launch techniques are described.

The 24 pilots (*W*) were grouped for flight experience (Table 1).

These 24 pilots (*W*) were also classified into three quantiles (tertiles) according to their individual aerobic capacities, identified by maximum oxygen uptake ($\dot{V}_{O_2}$ max) during exhausting bicycle ergometry (see Table 2).

Cardiopulmonary control values (rest) were determined spirometrically in the control period before bicycle ergometer work.

A double-seated glider airplane (Bergfalke II) was employed for the flight tests which consisted of a normal flight pattern between 6 and 20 minutes in length. The test protocol covered a preflight- (3 min), take-off- (1.5 min), inflight- (2.5 min), landing- (2 min), and postflight-phase (3 min).

The Oxycon P spirometric equipment (Mijnhardt) and the amplifier/tape storage system (Lennartz) were installed in the aircraft cockpit. The pilot was connected to the system through his breathing mask and -hose and ECG electrodes.

Heart rate (HR), respiration rate (RR), respiration minute volume ($\dot{V}_E$), and inspiratory-expiratory oxygen difference (ΔO_2; $F_{iO_2} - F_{eO_2}$) were continuously recorded. Oxygen uptake ($\dot{V}_{O_2}$) was calculated from $\dot{V}_E$ and ΔO_2. All

Table 1 "Group" classification of 24 pilots acc. to flight experience

Group	n	years	cm	kg	total hours	total flights
GR 1 1–25 h	7	25.4 ±4.4	181 ±3.5	71.6 ±8.3	11.6 ±9.7	61 ±40
GR 2 26–250 h	12	25.0 ±2.2	181.1 ±6.7	71.2 ±8.3	100.8 ±62.6	295 ±169
GR 3 > 250 h	5	31.5 ±6.9	181.6 ±7.4	69.8 ±6.4	680 ±305.4	1260 ±706

Table 2 "Quantile" classification of 24 pilots according to maximum oxygen uptake ($\dot{V}_{O_2}$max). Age related nominal values were taken into consideration

Quantile	n	years	cm	kg	W/kg	$\dot{V}_{O_2}$max/kg	
1. Tertile	8	25.2 ±3.0	181.4 ±5.7	65.4 ±3.2	4.7 ±0.4	3415 ±378	52.0 ±4.0
2. Tertile	8	30.4 ±5.7	177.6 ±3.5	70.1 ±5.1	3.9 ±0.5	3025 ±106	43.3 ±3.0
3. Tertile	8	23.9 ±2.2	184.3 ±6.0	76.9 ±8.9	3.6 ±0.3	3105 ±227	40.0 ±1.9

parameters were analyzed for 30 seconds intervals (total: 24 half minutes). Energy expenditure (EE) was calculated from oxygen uptake for each observation phase.

Statistical comparison of group and quantile differences was performed using the non-parametric Kruskal-Wallis Rank Variance analysis.

3. Results

3.1 General

Compared to control values (rest), all cardiopulmonary parameters, except ΔO_2, were increased during flight, gaining peak values during take-off and landing. ΔO_2 showed only small changes during all flight phases, countercurrent to respiration minute volume (Fig. 1, Table 3). In the flights started with winch tow (Fig. 3) preflight HR and respiration parameters were increased 50–70% compared to control values (rest), but $\dot{V}_{O_2}$ less of 40% increase. During take-off, increases of about 90% were noted in HR, RR, and $\dot{V}_{O_2}$, and of about 140% in $\dot{V}_E$. The gradual decrease of values started less than 60 seconds after take-off; in the flight phase, HR and respiration parameters levelled off at about 80% and $\dot{V}_{O_2}$ at 60% above resting values. From downwind leg to final landing approach progressive increase in all parameters were observed. At touch-down maximum values were measured which were similar to the maximum values during take-off. Postflight data are well comparable to preflight data. The general pattern of physiological reactions was similar in both launch techniques *winch (W)* and *aerotow (F)* (Fig. 2, Table 4; Fig. 3). While *W* showed more abrupt and brief increases, *F* led to a more gradual onset of changes of the parameters which remained elevated for about 2.5 minutes.

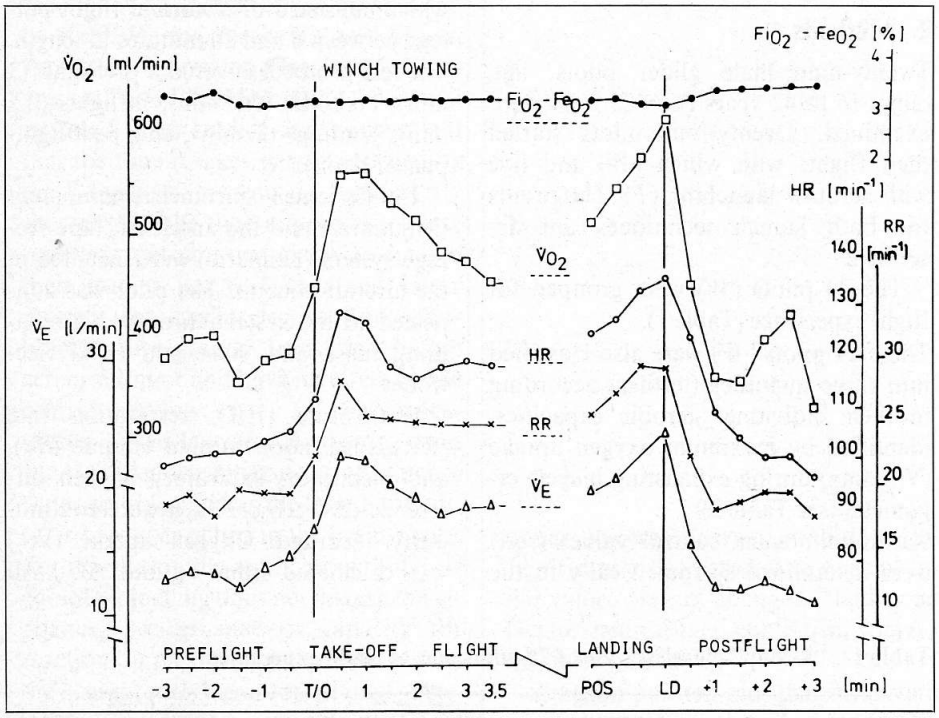

Fig. 1 Winch Towing: Synopsis of the cardiopulmonary parameters during short-duration glider flights (mean values; standard deviations, min. and max. values are listed in Table 3).

WINCH TOWING		HALF-MINUTE																						
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
$\dot{V}_E$ (l/min)	N=	16	11	12	17	22	23	24	24	24	23	23	20	20	19	24	24	24	24	16	15	14	10	7	8
	MAX	231	230	198	202	220	222	295	392	352	299	277	273	268	319	392	372	385	385	220	176	167	178	174	154
	MIN	66	73	90	75	73	68	75	70	97	98	79	86	86	79	70	81	132	108	68	53	68	68	68	68
	$\bar{x}$	128	135	134	123	139	147	158	223	222	203	191	179	183	185	196	206	251	241	155	120	120	126	117	106
	SD±	47	52	34	35	41	38	48	75	57	55	55	52	54	62	66	59	84	61	40	37	33	40	44	36
RR (min^{-1})	N=	18	9	13	17	22	23	24	24	24	24	23	23	23	19	24	24	24	24	16	15	13	10	7	10
	MAX	26	31	25	28	28	29	40	38	36	38	36	36	36	38	38	39	42	42	30	26	26	28	24	24
	MIN	12	14	13	12	14	10	16	11	13	14	10	14	14	15	17	16	16	18	14	10	12	12	12	12
	$\bar{x}$	186	192	178	199	195	195	223	281	255	252	249	247	247	248	255	272	294	293	222	181	185	193	193	116
	SD±	38	56	38	45	40	46	54	69	58	62	66	55	61	62	58	61	62	63	48	48	46	50	47	34
$\dot{V}_{O_2}$ (ml/min)	N=	10	8	10	15	21	22	24	24	24	23	22	20	20	15	24	24	24	24	17	15	12	8	5	3
	MAX	445	494	469	401	486	603	863	839	823	776	770	708	611	596	787	757	821	783	734	508	503	493	535	390
	MIN	304	267	304	216	226	217	267	273	398	325	310	325	245	319	275	368	432	432	310	180	233	275	248	231
	$\bar{x}$	379	398	399	336	373	381	446	559	562	533	515	484	472	453	512	546	574	614	449	358	352	395	418	330
	SD±	40	68	59	59	78	92	141	146	128	134	126	103	99	79	119	99	106	98	128	103	79	86	109	87
HR (min^{-1})	N=	15	12	14	18	20	24	24	24	24	24	23	23	22	18	24	24	24	24	21	18	14	9	8	6
	MAX	122	119	121	121	136	136	145	156	161	163	169	167	165	150	160	162	161	161	148	138	131	129	129	128
	MIN	78	84	83	83	88	77	77	100	97	82	74	73	76	85	87	89	88	89	74	68	84	85	84	79
	$\bar{x}$	99	101	101	102	104	106	112	129	127	119	116	118	120	119	125	128	134	136	124	109	104	100	100	96
	SD±	14	12	13	12	12	13	17	17	18	21	21	21	22	18	17	17	19	19	18	19	11	13	14	17

Table 3 Winch Towing: Changes in the cardiopulmonary parameters during short-duration glider flights.

3.2 Energy Expenditure (EE) (Fig. 4)

Compared to control values (rest) preflight EE was increased 30%. During take-off and landing 95 to 100% (*W, F*) increases were seen. During flight EE levelled at 70% above resting values. Postflight and preflight data were similar.

3.3. The Relevance of Individual Aerobic Capacity on Cardiopulmonary Function in Flight

After categorizing the 24 pilots (*W*) according to their individual aerobic capacity ($\dot{V}_{O_2}$max) (see Table 2), no significant diferences in the response of the cardiopulmonary parameters were identified during all flight phases. However, pilots with low aerobic capacities (QU III) tended to have higher mean values in HR and respiration parameters during take-off and landing.

3.4. The Relevance of Personal Flight Experience on Cardiopulmonary Function in Flight

In the flight test, all pilots, independently of flight experience, showed the general pattern of physiological reactions.

Table 5 "Bergfalke" glider airplane: leg and arm forces necessary to steer the airplane

Rudder pedals	7 kp – 30° bank, 75 km/h
Aileron (stick)	2.5 kp – 30° bank, 75 km/h
Stabilizer (stick)	2.5 kp – 30° bank, 75 km/h
	5.5 kp – Take-off (*W*) 90 km/h
Speed brakes (handle)	9–12 kp – initially

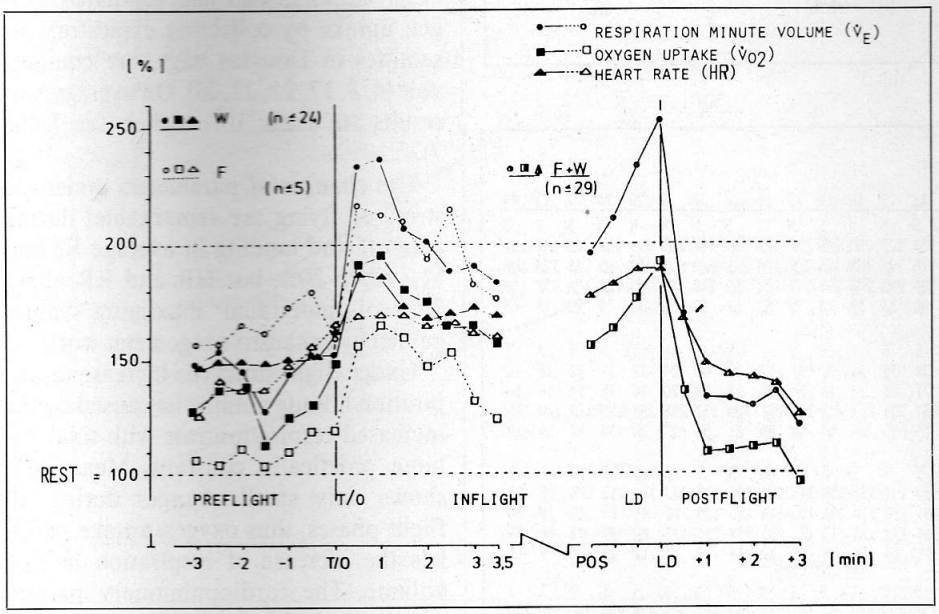

Fig. 2 Aerotow: Synopsis of the cardiopulmonary parameters during short-duration glider flights (mean values; standard deviations, min. and max. values are listed in Table 4).

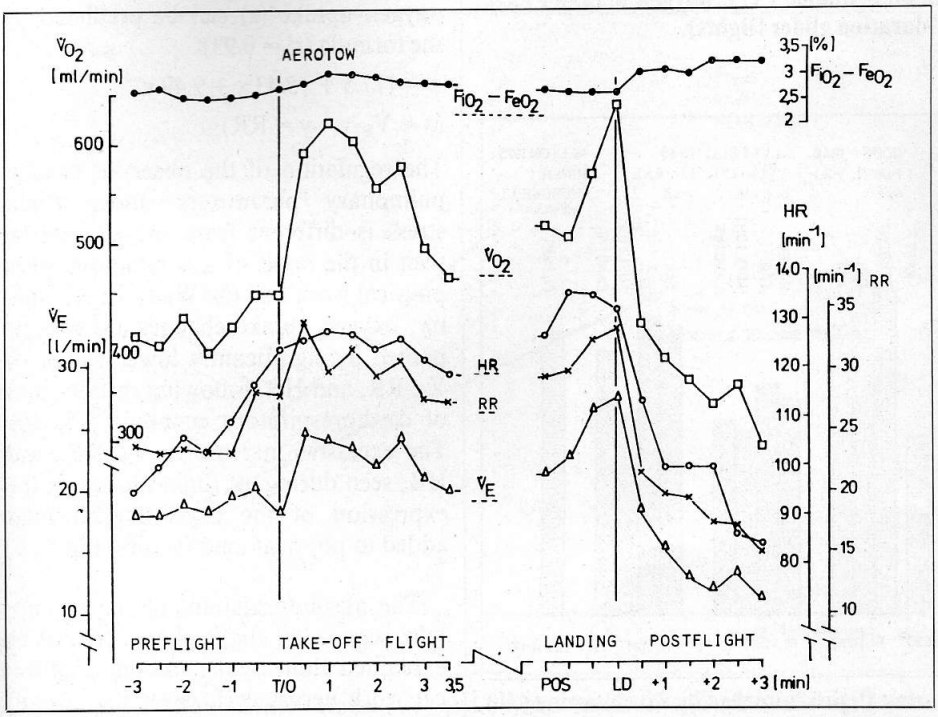

Table 4 Aerotow: Changes in the cardiopulmonary parameters during short-duration glider flights.

However, during take-off and landing the mean increases of RR, $\dot{V}_E$, and $\dot{V}_{O2}$ in highly experienced pilots (GR 3) remained at lower levels than in pilots of low (GR 1) or average (GR 2) flight experience. Group differences in $\dot{V}_{O2}$ and RR were significant ($p < 0.05$) in all minutes from take-off to touch-down, in $\dot{V}_E$ for several half minutes of take-off and flight. No significant group differences were seen in HR response.

3.5. Additional Results

Using a spring balance, the leg and arm forces necessary to steer the aircraft were measured (Table 5).

In a spirometric laboratory test equivalent arm and leg forces produced small but measurable changes in cardiopulmonary parameters (Table 6).

4. Discussion

4.1 General

The uniform alterations of the parameters (see Fig. 1, 2, 3) clearly demonstrate that take-off and landing cause the highest stress responses within the pilot workload in short duration glider flights. Landing seems to provide slightly higher stress than take-off. The two launch techniques *W* and *F* produce similar reactions in the cardiopulmonary dimension. In addition to physical work and psychological influences during *W*, short duration G_x and G_z accelerations and the changes in body position during climb-out must be considered as physical factors, leading to certain alterations in the cardiopulmonary parameters [1].

During *F* no positional or acceleration components are identified, but here the physical work necessary to steer the aircraft is considered higher than in *W*, due to a higher airspeed behind the towing aircraft.

During flight and landing physical work is estimated as rather low.

The increase of all parameters during landing is caused primarily by mental and emotional stress factors.

Elevated values pre- and postflight can be viewed as anticipatory stress and slow discharge of emotional load.

Referring to the literature our results demonstrate that glider pilots have slightly higher respiration rate (RR) [2, 9, 19], heart rates (HR) [14, 19, 28, 29, 30,

Table 6 Laboratory test simulating arm and leg forces necessary to steer the test glider airplane ($\bar{x}$)

	$\dot{V}_E$ (l/min)	$\dot{V}_{O_2}$ (ml/min)	AF (min^{-1})
Rest (n=4)	7.9	249	12
Arm work static 10 kp 3rd minute (n=4)	13.8	439	20

AERO-TOW		HALF-MINUTE																						
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
$\dot{V}_E$ (l/min)	N =	3	2	3	4	4	4	5	5	5	5	5	5	5	5	5	5	5	5	4	4	4	3	2	2
	MAX	216	180	211	205	235	233	242	343	332	312	284	323	260	284	255	328	367	367	249	211	157	165	147	125
	MIN	156	178	161	165	158	174	145	191	205	205	176	198	178	165	187	174	216	249	119	130	95	88	128	106
	$\bar{x}$	180	179	188	183	197	204	182	248	242	237	220	244	208	200	215	228	269	278	185	155	131	124	138	116
	SD^{+}_{-}	30	01	25	19	35	24	39	57	54	43	40	53	34	48	32	59	57	50	54	38	29	39	13	13
RR (min^{-1})	N =	3	2	3	4	4	5	5	5	5	5	5	5	5	5	5	5	5	5	4	4	4	3	2	2
	MAX	28	24	28	26	24	34	32	46	38	40	38	36	34	34	37	37	40	40	24	22	24	22	18	16
	MIN	20	22	18	18	22	24	24	27	22	26	21	23	20	18	24	20	28	28	20	16	16	14	16	14
	$\bar{x}$	237	230	233	230	230	280	278	338	298	316	294	306	274	272	294	298	324	332	215	198	195	173	170	15
	SD^{+}_{-}	40	14	50	35	12	37	30	88	67	61	73	56	65	63	52	69	61	56	17	26	34	42	14	14
HR (min^{-1})	N =	3	3	3	4	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4	2	2
	MAX	99	106	113	113	131	134	136	138	153	141	139	141	136	136	145	163	156	145	127	114	113	122	92	91
	MIN	92	90	96	88	88	104	104	108	100	108	105	110	110	101	106	114	120	120	102	83	83	80	79	76
	$\bar{x}$	94	99	106	102	108	115	123	125	127	126	123	125	120	118	126	135	134	131	112	99	99	99	86	84
	SD^{+}_{-}	4	8	9	12	16	12	13	19	22	15	15	13	14	16	16	21	16	12	13	12	12	17	9	11
$\dot{V}_{O_2}$ (ml/min)	N =	3	2	3	4	4	4	5	5	5	5	5	5	5	5	5	5	5	5	3	3	3	2	1	1
	MAX	585	457	536	538	452	554	677	709	683	722	716	859	670	562	601	352	747	773	435	429	450	397	360	296
	MIN	307	330	337	272	307	369	353	468	539	498	401	455	383	370	408	680	357	532	385	330	299	277	360	296
	$\bar{x}$	403	394	420	387	413	446	446	585	619	601	551	575	493	464	516	505	568	642	418	385	353	337	360	296
	SD^{+}_{-}	158	90	104	120	71	89	132	89	64	83	119	168	106	76	93	118	141	120	29	50	84	85	000	000

Fig. 3 Percentage changes of respiration minute volume ($\dot{V}_E$), oxygen uptake ($\dot{V}_{O_2}$), and heart rate (HR) under flight stress (short-duration glider flights).

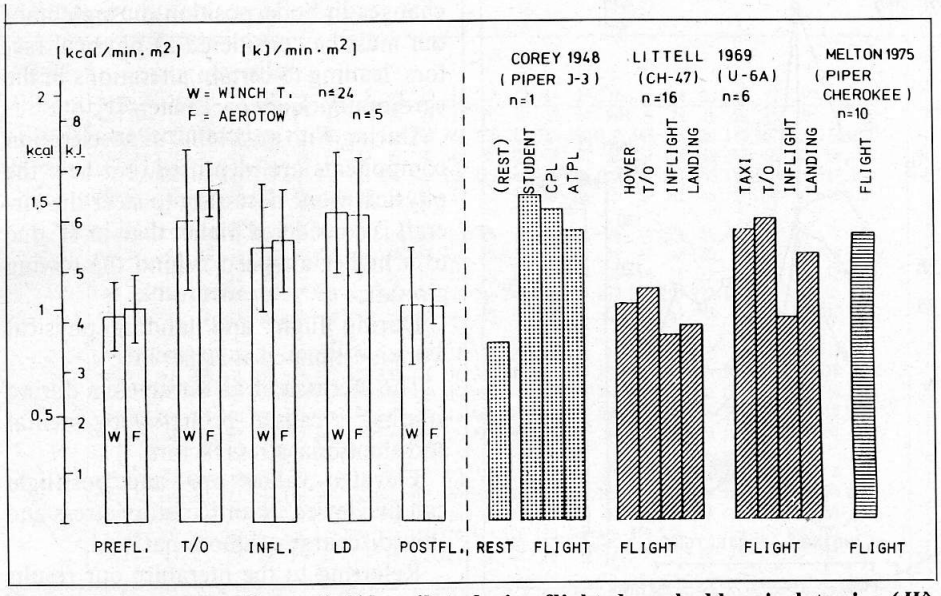

Fig. 4 Energy expenditure of glider pilots during flights launched by winch towing (*W*) and aerotow (*F*), compared to caloric cost of different pilot groups flying other types of aircraft (right side; results compiled from literature).

33], and respiration minute volumes ($\dot{V}_E$) [8, 11, 23, 24, 27] than pilots of other aircraft, but in most of the quoted studies highly experienced professional pilots were examined.

Continuous measurement of oxygen uptake of pilots during real flight has not been previously reported. The results of other authors, who had evaluated oxygen uptake by collecting expiratory air samples in Douglas bags, are comparable [4, 8, 17, 21, 22, 23]. On average, our results are about 10% higher (see Table 7).

The changes of parameters under the stress of flying are remarkable; during take-off and landing in average $\dot{V}_E$ and $\dot{V}_{O_2}$ reach 20%, but HR and RR about 70% of individual maximum values gained by exhaustive ergometer work.

Under flight stress the increase in respiration minute volume ist caused by the increased respiration rate with tidal volume practically constant. Mean ΔO_2 shows only small changes during all flight phases; thus oxygen uptake parallels the increase of respiration minute volume. The cardiopulmonary parameters measured here are closely correlated. With multiple linear regression, using respiration rate and respiration minute volume as independent variables, oxygen uptake (z) can be predicted by the formula ($r^2 = 0.93$):

$$z = 117.5 + 15.43\,x + 9.49\,y$$

($x = \dot{V}_E$ $\quad y = RR$)

The regulation of the observed cardiopulmonary parameters under flight stress is different from the adaptation seen in the onset of a comparable pure physical workload (50 Watt). In ergometry, oxygen uptake changes are accompanied by significantly lower values of $\dot{V}_E$, RR, and HR, following certain rules of cardiorespiratory economy [15, 16]. The excessive increase in $\dot{V}_E$, RR, and HR, seen during all flight phases, is the expression of the psychological load added to physical load factors (Fig. 5, 6, 7).

The absolute amount of oxygen uptake seen in all flight phases cannot be explained alone by the amount of physical work necessary to steer the aircraft (see Tables 5 and 6). Parts of the oxygen consumption must be attributed to an in-

crease in muscle tone due to psychic excitation [8]. Furthermore, additional oxygen uptake is needed for the overproportional increase of ventilation.

In some of our pilots, the marked response of the ventilation parameters during take-off and landing, far beyond the requirements of piloting, lets us assume the presence of hyperventilation, often described as hazardous to flight safety [2, 3, detailled lit. see 11]. Hyperventilation of 30–40 l/min as seen in some of our pilots, can lead to considerable decrease of cerebral perfusion [18]; psychomotor performance may be reduced and reaction time be prolonged [34, see 11]. Further investigation is necessary in this field.

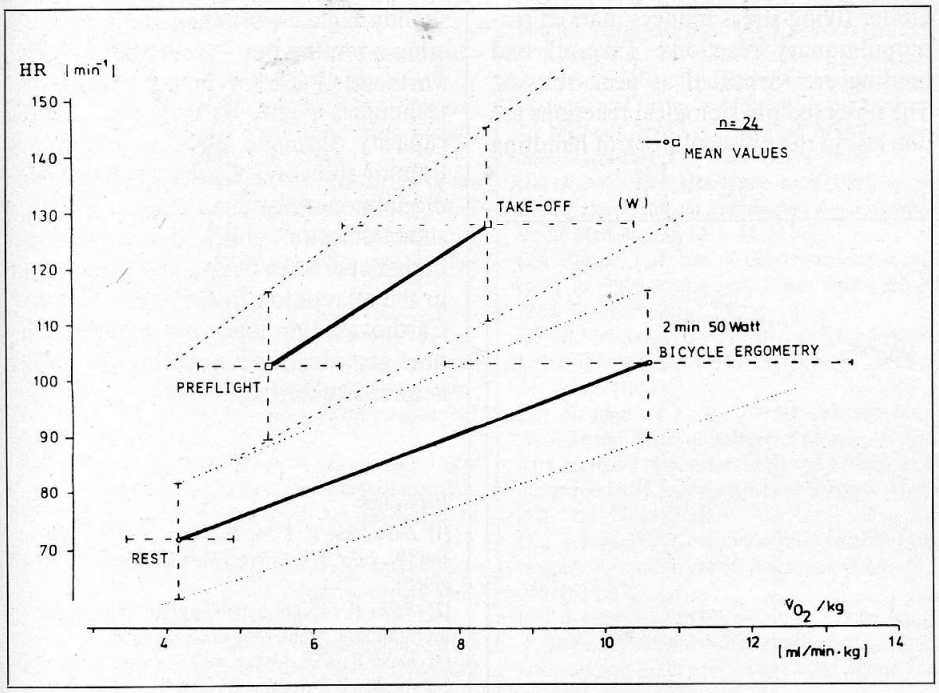

Fig. 5 Heart rate (HR) and oxygen uptake ($\dot{V}_{O_2}$/kg)-relationship during take-off (winch towing) and, in comparison, during onset of ergometer work (50 Watt).

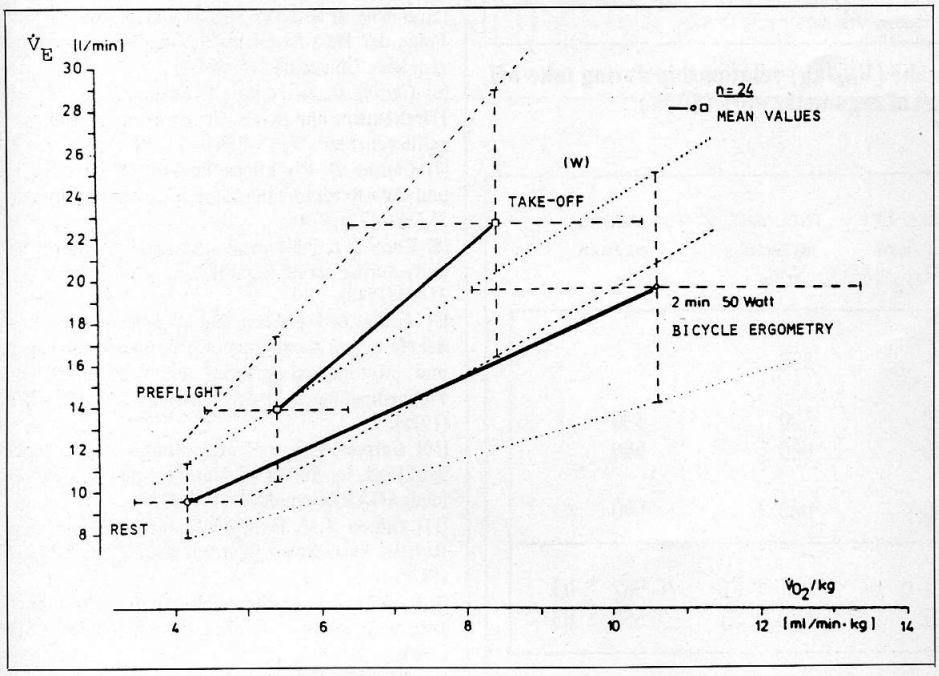

Fig. 6 Respiration minute volume ($\dot{V}_E$) and oxygen uptake ($\dot{V}_{O_2}$/kg)-relationship during take-off (winch towing) and, in comparison, during onset of ergometer work (50 Watt).

In several of the test subjects heart rate values above 160/min during take-off and landing depict a remarkable cardiovascular load, showing that heart rates in presumably healthy individuals can reach values in the neighborhood of age-related maximum heart rates. We therefore emphasize the necessity to carry out an exercise stress test as part of the pilot medical examinations, sufficient to induce a heart rate response at or above 70% of age related nominal maximum values.

4.2 Endurance Training and Cardiorespiratory Function Inflight

A great number of pilots who participate in competition or performance gliding, conduct many forms of endurance training. Yet it is not known whether improved aerobic capacity provides any advantage in the stress adaptation to flying. According to Wegmann [35] who tested the effects of improved aerobic capacity on several forms of stress, the advantages of endurance training are not transferable to stresses other than physical work. This is supported by SARIJAVIU (1971) [31] who did not find differences in catecholamine excretion in aerobatic pilots before and after endurance training. The results in our study support the conclusion that improved aerobic capacity (by endurance training) does not play a measurable role in the cardiopulmonary adaptation to the stress of flying. This statement can be applied only to short-duration flights; the value of improved aerobic capacity with regard to the complex of «fatigue», apparent in long-duration flights, needs further investigation.

4.3 Flight Experience and Cardiorespiratory Function Inflight

According to the literature personal

flight experience influences inflight heart rate response in a favourable way [see 12]. Our results confirm that the cardiopulmonary parameters measured here are similarly influenced by flight experience. Respiration rate is found to be the most sensitive parameter to identify differences between pilot groups of different flight experiences. However, heart rate, used by many authors as the single criterium to evaluate pilot workload, was not appropriate to discriminate pilot group differences in our experiment due to the high interindividual dispersion of values.

5. Conclusion

Glider flying stress induces marked cardiopulmonary reactions. Take-off and landing are identified as peak stresses. The observed physiological reactions are due less to the physical work of handling the aircraft, but more to psychological stress. Increase of oxygen uptake is partly caused by an isometric increase in the muscle tone. Although glider flying is considered as light physical work (<25% of $\dot{V}_{O_2}$max), glider pilots seem to have slightly higher workloads than pilots of other aircraft types. Psychophysiological workload is similar in the two launch techniques *F* and *W*. Improved aerobic capacity through physical endurance training shows no clear advantage in cardiopulmonary system's responses during short duration glider flying. Personal flight experience plays a perceptible role in the adaptation to the stress of flying. Cardiovascular load and hyperventilation are identified as items of special aeromedical interest.

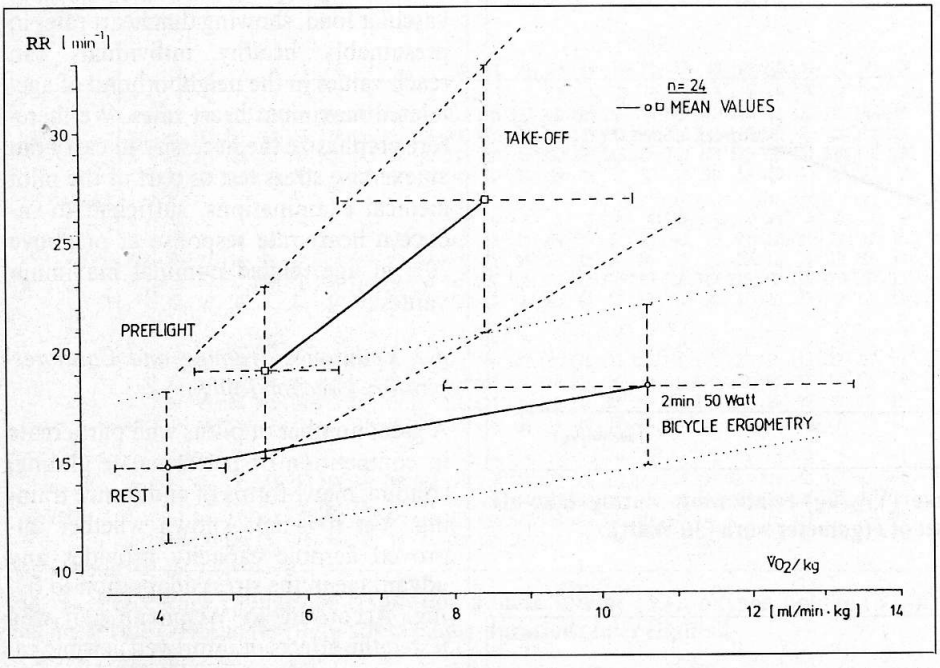

Fig. 7 Respiration rate (RR) and oxygen uptake ($\dot{V}_{O_2}$/kg)-relationship during take-off (winch towing) and, in comparison, during onset of ergometer work (50 W).

Author	Preflight ml/min $\dot{V}_{O_2}$	Take-Off ml/min $\dot{V}_{O_2}$	Inflight ml/min $\dot{V}_{O_2}$	Landing ml/min $\dot{V}_{O_2}$
Karpovich 1946				
-simulator			356	
Litell 1969				
-helicopter	330	420	320	390
-prop. plane	360	580	400	500
Billings 1970				
-helicopter	420	540	460	540
own data				
-W	387 ± 33	551 ± 16	481 ± 26	562 ± 43
-F	415 ± 24	601 ± 17	520 ± 51	558 ± 63

Table 7 Oxygen uptake ($\dot{V}_{O_2}$) measured in pilots of different classes of aircraft (results compiled from literature and own data).

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Zusammenfassung

Die Belastung von Segelflugpiloten ist zusammengesetzt aus psychischen und physischen Anteilen. Um die Anteile dieser Faktoren an den biologischen Gesamtveränderungen beim Fliegen qualitativ und quantitativ zu erfassen, wurden mehrere kardiopulmonale Parameter simultan bei 29 Segelflugpiloten unter fliegerischen Bedingungen gemessen. Anhand der Herz-Kreislauf- und Atemparameter wurden Start und Landung als Stressmaxima identifiziert; dabei sind die Stressreaktionen bei Winden- und Flugzeugschleppstart vergleichbar. Die für das Mass für die körperliche Arbeit beim Steuern des Segelflugzeugs hinaus erheblich gesteigerten Veränderungen der untersuchten Parameter sind als Folge der psychischen Belastung zu interpretieren. Die individuelle kardiozirkulatorische Leistungsfähigkeit (Ausdauertrainingszustand) ist für die Einstellung der untersuchten Parameter unter der psychophysischen Belastung der kurzzeitigen Segelflüge ohne erkennbare Bedeutung. Dagegen nimmt die Flugerfahrung Einfluss auf die Höhe der flugphasenspezifischen Veränderungen einzelner Messgrössen im Sinne adäquater Anpassung. Die Bedeutung hinsichtlich der Flugsicherheit wird diskutiert.