Progressive Hypoglycemia's Impact on Driving Simulation Performance

Occurrence, awareness, and correction

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OBJECTIVE — Progressive hypoglycemia leads to cognitive-motor and driving impairments. This study evaluated the blood glucose (BG) levels at which driving was impaired, impairment was detected, and corrective action was taken by subjects, along with the mechanisms underlying these three issues.

RESEARCH DESIGN AND METHODS — There were 37 adults with type 1 diabetes who drove a simulator during continuous euglycemia and progressive hypoglycemia. During testing, driving performance, EEG, and corrective behaviors (drinking a soda or discontinuing driving) were continually monitored, and BG, symptom perception, and judgement concerning impairment were assessed every 5 min. Mean ± SD euglycemia performance was used to quantify *z* scores for performance in three hypoglycemic ranges (4.0–3.4, 3.3–2.8, and <2.8 mmol/l).

RESULTS — During all three hypoglycemic BG ranges, driving was significantly impaired, and subjects were aware of their impaired driving. However, corrective actions did not occur until BG was <2.8 mmol/l. Driving impairment was related to increased neurogenic symptoms and increased theta-wave activity. Awareness of impaired driving was associated with neuroglycopenic symptoms, increased beta-wave activity, and awareness of hypoglycemia. High beta and low theta activity and awareness of both hypoglycemia and the need to treat low BG influenced corrective behavior.

CONCLUSIONS — Driving performance is significantly disrupted at relatively mild hypoglycemia, yet subjects demonstrated a hesitation to take corrective action. The longer treatment is delayed, the greater the neuroglycopenia (increased theta), which precludes corrective behaviors. Patients should treat themselves while driving as soon as low BG and/or impaired driving is suspected and should not begin driving when their BG is in the 5.0–4.0 mmol/l range without prophylactic treatment.

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While there are no clear data demonstrating that patients using insulin have a higher incidence of motor vehicle crashes (1–4), there is little debate that hypoglycemia produces cognitive-motor impairments at blood glucose (BG) levels around 3.6 mmol/l (5,6) and that progressive neuroglycopenia will impair driving. The role of hypoglycemia in impaired driving can be inferred by two recent studies. Blood Glucose Awareness Training (BGAT), an 8-week psychobehavioral training program that increases awareness of BG fluctuations and results in fewer and less extreme low BG events, has led to fewer motor vehicle crashes at long-term follow-up (4.3 years) compared with a control group (1). A 12-month follow-up of BGAT-2, a revised version of BGAT, demonstrated a 67% reduction in motor vehicle violations (1).

During direct investigation of the effects of hypoglycemia on driving performance using a driving simulator, driving impairments have been documented at moderate hypoglycemia (2.5 mmol/l), but not at mild hypoglycemia (3.6 mmol/l) (1). These effects were found to be reliable at retesting (1). However, these studies used a relatively simple single-screen driving simulator, testing 5 min of driving performance during stepped hypoglycemia. This stepped hypoglycemia methodology had the following two limitations: *1*) in a natural environment, hypoglycemia is assumed to be progressive and not a stepped process, and *2*) it is assumed that hypoglycemia occurs while driving and is not necessarily present at the time of driving initiation.

Prevention of hypoglycemia-related driving crashes relies on both a driver's ability to recognize his/her driving impairments and then immediately take the corrective actions of consuming carbohydrates and/or pulling off the road. The ability of individuals to make and execute these decisions and what contributes to such decision-making and behaviors has not been investigated.

In an attempt to address these methodological limitations and self-regulation processes, driving performance during euglycemia and progressive hypoglycemia was compared with a sophisticated driving simulator. Three general issues investigated were *1*) the BG level at which driving impairment is first observed, *2*) the BG level at which patients detect driving impairments and take the corrective action of either consuming glucose or discontinuing driving, and *3*) the mechanisms underlying both driving impair-

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Abbreviations: BG, blood glucose; BGAT, Blood Glucose Awareness Training; NASA, National Aeronautics and Space Administration.
A table elsewhere in this issue shows conventional and Système International (SI) units and conversion factors for many substances.

Table 1—*Subject characteristics for those with and without a recent history of severe hypoglycemia*

	No history of severe hypoglycemia	≥2 episodes of severe hypoglycemia in past 12 months	*P*	All subjects
n	14	23	—	—
Age (years)	33.4 ± 4.7	36.5 ± 8.1	0.21	35.3 ± 7.1
Duration of diabetes (years)	16.0 ± 11.8	18.5 ± 8.8	0.47	17.5 ± 10.0
Impaired/normal hypoglycemia awareness	4/10	14/9	0.12	18/19
Sex (M/F)	7/7	9/14	0.75	16/21
Units of insulin per day per kilogram	0.64 ± 0.17	0.59 ± 0.17	0.34	0.61 ± 0.17
HbA_1	8.6 ± 1.3	8.4 ± 2.0	0.74	8.5 ± 1.8
BMI	25.5 ± 4.1	23.0 ± 3.1	0.04	23.9 ± 3.7
Auto crashes per 1,000,000 miles	20.1 ± 56	43.2 ± 161	0.62	34.7 ± 131
Motor vehicle violations per 1,000,000 miles	20.1 ± 46	43.0 ± 109	0.38	34.3 ± 90.1
Average miles driven/year	13,594 ± 11,147	6,839 ± 3,951	0.04	9,395 ± 8,089

Data are *n* or means ± SD.

ments and awareness/correction of driving impairments.

RESEARCH DESIGN AND METHODS

Subjects

The study consisted of 37 subjects recruited through newsletters, notices posted in diabetes clinics, and direct physician referral. All subjects had to have diabetes for at least 2 years, have taken insulin since the time of diagnosis, be current drivers, and not be taking medications that might influence hypoglycemia or driving performance. There were 16 men and 21 women, with a mean (± SD) age of 35.3 ± 7.1 years, mean duration of disease 17.5 ± 10.0 years, mean insulin units per kilogram per day 0.61 ± 0.17, and mean glycosylated hemoglobin 8.5 ± 1.8%. The glycosylated hemoglobin assay was determined by a boronate affinity column chromatography method, with nondiabetic levels <6.9%. Upon physical examination, two subjects were found to have postural hypotension. Of the subjects, 23 had a history of two or more episodes of severe hypoglycemia in the past year, and 14 had no recent history of severe hypoglycemia; 18 satisfied the criteria of reduced hypoglycemic awareness (1), and 19 had normal awareness of hypoglycemia. Hypoglycemia awareness was assessed using a 0–4 Likert scale (0 = never, 1 = rarely, 2 = sometimes, 3 = often, 4 = always) for the question "To what extent can you tell by your symptoms that your blood sugar is LOW?" Using this scale, a score of <2 has been shown to be associated with impairment of hypoglycemia awareness (11) (Table 1).

Procedure

All subjects attended orientation meetings and signed consent forms. Subjects were admitted to the University of Virginia's General Clinical Research Center the evening before the study. That evening, subjects received a physical exam, were introduced to the simulator and its operation, and were allowed to drive the simulator for a minimum of 15 min, or as long as needed for the subject to report feeling comfortable with its operation. While driving the simulator, subjects practiced rating their symptoms and driving performance on a 0–6 scale, were shown a bottle of orange soda (the contents were actually diet soda) in the glove compartment, and were instructed to drink the soda or pull off the road and discontinue driving if they thought their BG was too low.

BG was maintained overnight between 5.6–8.3 mmol/l with intravenous regular human insulin as per a previously published insulin infusion protocol (2). Subjects were given dinner and a bedtime snack the evening before the study, but remained fasting on the morning of the study. No caffeinated beverages were consumed after hospital admission.

On the morning of the study, intravenous lines were placed in the nondominant forearm. Insulin was continuously infused at a constant rate of 1.0 $mU \cdot kg^{-1} \cdot min^{-1}$, and a 20% dextrose solution was infused at a variable rate to maintain BG between 5.6 and 8.3 mmol/l for the first hour of testing and then progressively lowered to a BG of 2.2 mmol/l. Adjustments in dextrose infusion were made every 5 min to achieve a fall in BG of 1 $mmol \cdot l^{-1} \cdot 15\ min^{-1}$. The protocol was discontinued once because of severe lethargy, disorientation, and confusion. (This subject was then dropped from the study.) Arterialized blood (achieved by warming the hand in a heated glove to 50°C) was sampled for glucose concentration every 5 min. At the time of every BG sample, subjects rated on a seven-point scale (0 = none, 6 = extreme) four neurogenic symptoms (jittery or tense, pounding heart, trembling, sweating), four neuroglycopenic symptoms (difficulty concentrating, uncoordination, visual disturbance, light headed or dizzy), "need to treat right now," and "difficulty driving." Finally, subjects estimated their BG level.

During the first hour, subjects watched a videotape of someone else driving the simulator and drove the simulator themselves for 30 min each. This video condition controlled for our data collection procedure. The order of watching/driving was randomized. Euglycemia while driving served as the control condition against which individual effects of hypoglycemia were compared. The second 30 min of driving began when the BG level reached ~4.0 mmol/l. Euglycemia testing always preceded hypoglycemia testing for the following two reasons: *1*) if neuroglycopenia persisted beyond hypoglycemia, we did not want it operative during the euglycemia test, and *2*) if there were practice effects with the driving simulator, then the more conservative approach would be to have these operative during hypoglycemia. Figure 1 presents the design of the study. Patients were kept blind to the BG manipulations and actual BG levels. They were instructed that the study was investigating the effects of high and low BG on brain wave activity and driving behaviors.

Driving simulator

To objectively assess driving in a controlled environment, the Atari Research

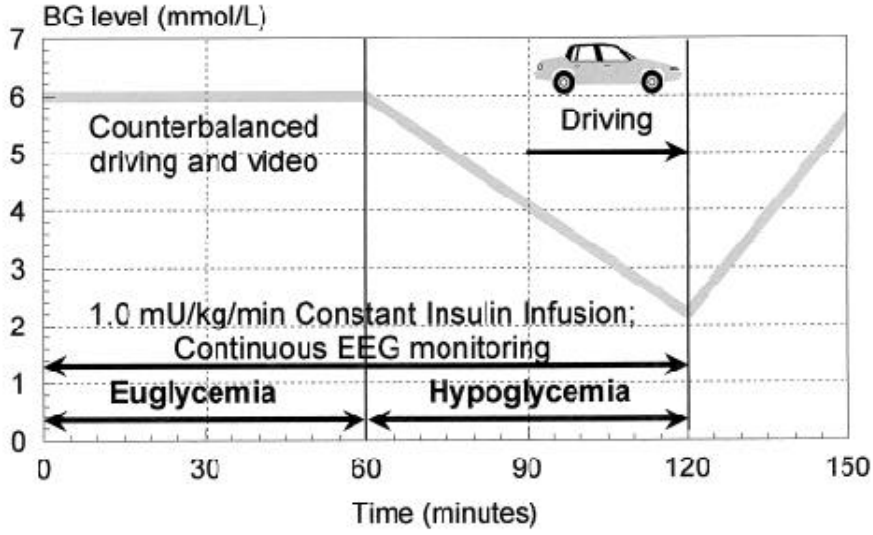

Figure 1—*Experimental design: BG manipulations and dependent variables.*

Driving Simulator was used. It is a realistic, interactive, fixed platform simulator that generates accurate and sensitive driving performance data (Fig. 2). The current three-screen version of the simulator has been used to differentiate *1*) visually compromised drivers from control subjects (2–5), *2*) outpatients with Alzheimer's disease from age-matched control subjects (6), *3*) young adults with and without attention deficit/hyperactivity disorder on placebo versus Ritalin (6), *4*) middle-aged and senior males both when sober and intoxicated (6), and *6*) elderly from very elderly drivers (D.J.C., B. Kiernan, B.P.K., J. Guerrier, A. Gulliano, C. George, unpublished observations). Additionally, performance on this simulator has correlated with age-sensitive cognitive-motor testing, actual on-road driving performance, and occurrence of future auto crashes (6–8).

The simulator has three 25-in computer screens that wrap around the driver, providing a 160-degree visual field, along with a programmed rearview mirror depicting rear traffic. The driving environment is realistic, incorporating a typical-sized steering wheel, gas and brake pedals, seat, and seat belt. Driving performance feedback was provided to the subject visually through the three screens, which updated at a rate of 60 times/s; auditory feedback was provided through quadraphonic speakers delivering engine, tire, and road noises; and kinesthetic feedback was provided through the steering wheel and pedal pressure.

The driving course was designed to simulate driving demands of a typical grade 2 U.S. highway (Virginia Department of Transportation). The 16-mile course took ~30 min to traverse when following the posted speed limits. Table 2 lists the driving demands.

The simulator records data four times a second and generates the nine driving performance variables listed in Table 3. There are three steering controls, three braking, and three speed control driving performance variables (2).

Awareness and corrective behaviors

At each 5-min BG sampling, subjects were read aloud the symptoms and the driving impairment items. Subjects gave their 0–6 ratings orally. To cue subjects, the seven-point scale was posted just above the simulator's center screen. The researcher also recorded whether the subject drank the glucose drink and/or pulled the car off the road.

EEG analysis

An appropriately sized EEG cap (Electrode Cap International, Eaton, OH) was placed over the subject's head. Six electrode sites were prepared: a ground just in front of C_Z, an earlobe reference electrode, and C_Z, P_Z, P_3, and P_4. The impedance criterion was 10 K ohms, as measured by a Prep-Check electrode impedance meter. The EEG equipment was provided by the National Aeronautics and Space Administration (NASA) (Langley, VA), whose researchers investigating the attention of pilots in flight simulators recommended sites and impedance criteria (7,8). EEG signals were amplified and processed by the Biopac system, and on-line data analysis was accomplished using the CREW (Crew Response Evaluation Window;

Figure 2—*Atari Research Driving Simulator.*

Table 2—*Driving demands during the 16-mile course*

	Frequency
Left turns (driver needs to turn left at specific stop-sign intersections, negotiating oncoming and cross traffic)	5
Red lights (driver needs to stop)	4
Green lights (driver has throughway)	8
Stop signs (driver needs to stop)	12
Throughway stop sign intersections (side-traffic stops)	8
Speed limit changes (driver needs to change speeds)	22
Sudden stops (e.g., car in front of driver slams on brakes, object in road comes into view as driver crosses hill crest, car runs red light from left side)	4
Detours at stop sign intersections (driver needs to obey detour arrow)	8
Encroaching fixed objects (vehicle parked in driver's lane)	2

NASA) system. The EEG signal was digitized from the four input channels at a rate of 200 samples/s into a circular buffer. Data were taken from the buffer in four data arrays of 512 data points each, i.e., at this sample rate, 2.56 s of data were analyzed at a time for each input channel. Standard time series techniques were used for this initial data retrieval: each array was smoothed using a Tukey-Hanning window, and the power spectrum was estimated using a fast Fourier transformation (7). Then the total power was computed for each of three EEG bands: theta 4–8 Hz, alpha 8–13 Hz, and beta 13–22 Hz. The residual power was carried by the frequencies 1.6–4 Hz and 23+ Hz. The band powers were normalized to produce percent power for each band and percent residual power. This procedure resulted in 12 EEG parameters, the percentage power in three bands for four electrode sites computed on 2.56-s data chunks.

RESULTS

Hypoglycemia and driving impairment

Based on the subject's mean euglycemic performance, *z* scores were calculated for each subject for each continuous variable for three BG ranges (4.0–3.4, 3.3–2.8, and <2.8 mmol/l) during the hypoglycemia condition. Collisions and percent missed stops, which may or may not have been possible within a specific BG range, were analyzed by comparing the last 15 min of the euglycemic and hypoglycemic conditions. The last 15 min ensured that all of the hypoglycemia data were collected when BG was <4 mmol/l.

As seen in Table 4, compared with euglycemic driving, during hypoglycemia, subjects engaged in more driving across the midline (risk midline: $P < 0.01$ with BG <2.8 mmol/l) and more speeding (high speed: $P < 0.01$ with BG between 4.0 and 2.8 mmol/l) and used brakes more on the open road (inappropriate braking: $P < 0.01$ with BG between 4.0 and 2.8 mmol/l). If we consider that there are a variety of impaired driving parameters occurring simultaneously and combining to contribute to dangerous driving, then we can sum the separate *z* scores for a Composite Driving Impairment score for each subject. By definition, the Composite Driving Impairment score for euglycemia would be 0, which was significantly different from the hypoglycemic Composite Driving Impairment score during all three BG ranges ($P < 0.01$), but did not get progressively worse with progressive hypoglycemia ($P = 0.45$, Table 4). There were 14 subjects (38%) who demonstrated extreme impairments in their driving, with a Composite Driving Impairment score >2 SD (98th percentile) worse than their euglycemic performance (Table 4).

Because research has demonstrated that hypoglycemic cognitive-motor deficits manifest at different BG levels for different subjects and that some patients may show adaptation to acute hypoglycemia (7), we compared the highest (worst) *z* score from one of the three hypoglycemic BG ranges for each driving parameter for each subject with the euglycemic *z* score of 0. For example, subject A might have driven off-road most at the 4.0–3.4 mmol/l range, subject B at the 3.3–2.8 mmol/l range, and subject C at the <2.8 mmol/l range, so that these three scores would be used in the comparison with euglycemia. As seen in Fig. 3, the driving parameters were each significantly impaired during some level of hypoglycemia, with off-road driving, driving fast, and applying brakes on the open road being most likely to occur. The mean Composite Driving Impairment of these worse scores was 3.3 (99.9th percentile), which was significantly worse than euglycemia ($t = 4.84$, $P < 0.001$). This indicates that at one of the three hypoglycemia BG ranges, driving performance was 3.3 SDs worse than the subject's average euglycemic performance.

When compared with the last 15 min of euglycemia, during the last 15 min of hypoglycemia subjects failed to stop at stop

Table 3—*Measured driving performance variables and explanations*

Driving variable	Explanation
Steering	
SD steering	Standard deviation of steering wheel angle while on road, swerving
Off-road	Number of times drove off road
Risk midline	Quadratic risk function that increases the longer and further the car crosses the midline
Braking	
Inappropriate braking	Inappropriate braking when car is in 35-mph, 45-mph, and acceleration zones
% Missed stops	Percentage of missed stop signs and stoplights
% Collisions	Percentage of collisions per potentially risky zone
Speed control	
Low speed	Average percentage below speed limit when car is in 35- and 45-mph speed zones
High speed	Average percentage above speed limit when car is in 35- and 45-mph speed zones
SD speed	Standard deviation of speed in 35 and 45 mph zones

Table 4—*Performance at three levels of hypoglycemia based on* z *scores derived from individual euglycemic performance*

Variable	BG 4.0–3.3	BG 3.3–2.8	BG <2.8
Driving performance *z* score deviation from euglycemia			
SD steering	0.04 (NS)	−0.02 (NS)	−0.04 (NS)
Off-road	0.25 (NS)	0.45 (NS)	0.57 (NS)
Risk midline	0.05 (NS)	0.17 (<0.1)	0.11 (<0.01)
Low speed	0.01 (NS)	−0.05 (NS)	0.37 (NS)
High speed	0.23 (<0.01)	0.56 (<0.001)	0.26 (NS)
SD speed	−0.09 (NS)	0.09 (NS)	0.23 (NS)
Inappropriate braking	0.0 (NS)	0.61 (<0.05)	0.00 (NS)
Composite driving impairment score	0.83 (<0.01)	1.83 (<0.005)	1.52 (<0.005)
% Subjects significantly impaired	12	26	16
Awareness deviation from euglycemia			
Difficulty driving rating	0.30 (<0.05)	0.35 (<0.1)	0.54 (<0.01)
% Subjects who detected their driving impairment	21	22	25
% Subjects who detected hypoglycemia	15	33	79
Corrective behaviors			
Self-treated (*n*)	2 (NS)	1 (NS)	8 (<0.05)
Stop driving (*n*)	1 (NS)	1 (NS)	5 (NS)
% Subjects who took corrective action	5	3	22
EEG power *z* score deviations from euglycemia			
θ (4–8 Hz)	0.01 (NS)	0.16 (NS)	0.76 (<0.001)
α (8–13 Hz)	0.10 (NS)	0.40 (<0.001)	0.80 (<0.001)
β (13–22 Hz)	−0.02 (NS)	0.30 (<0.001)	0.42 (<0.001)

P values are in parentheses.

signs significantly more often (4 vs.1%, $P = 0.01$) and were involved in more crashes at sudden stops (five subjects had sudden-stop accidents during hypoglycemia compared with only one subject during euglycemia, $\chi^2 = 2.9$, $P = 0.08$).

Awareness and corrective behaviors

A similar *z* score transformation was performed on the 0–6 self-reported impaired driving ratings. Similar to the objective Composite Driving Impairment score, these global self-evaluations were significantly elevated during mild and moderate hypoglycemia (Table 4).

There were 11 subjects who treated themselves during hypoglycemia (3 treated themselves twice), whereas during euglycemia, 3 subjects treated themselves ($P < 0.02$). The mean BG level at which subjects treated themselves during hypoglycemia was 2.7 ± 0.5 mmol/l (range 2.1–3.6). Likewise, seven subjects stopped driving during hypoglycemia (three stopped twice), whereas two stopped driving during euglycemia ($P = 0.07$). The mean BG level at which subjects stopped driving during hypoglycemia was 2.7 ± 0.4 mmol/l (2.3–3.6). A total of 12 vs. 3 subjects treated themselves and/or stopped driving during hypoglycemia versus euglycemia ($P < 0.01$). A χ^2 test comparing those driving impaired (Composite Driving Impairment score <2 vs. ≥2) and corrective behaviors (yes vs. no), found that those demonstrating significant impairments were more likely to take some form of corrective action ($\chi^2 = 8.10$, $P < 0.005$). However, in this analysis, 6 of the 14 (43%) severely impaired subjects did not take corrective action.

Underlying mechanisms

To determine factors contributing to poor driving, we first quantified the effects of hypoglycemia on EEG. During hypoglycemia, a significant progressive increase of the power of beta-, alpha-, and theta-frequencies was observed ($P < 0.01$). As indicated in Table 4, the power of beta increased early in the 3.3–2.8 mmol/l BG range and remained at that level, while alpha increased but continued to increase more as BG fell below 2.8 mmol/l and theta did not begin to increase until BG fell below 2.8 mmol/l.

The Composite Driving Impairment score was the dependent variable in multiple regressions through the origin in which the predictor variables were theta, alpha, and beta *z* scores, self-reported neuroglycopenic and neurogenic symptom *z* scores, and estimated BG level. At mild to moderate hypoglycemia (BG 4.0–2.8 mmol/l), a significant regression model ($F = 18.3$, $P < 0.0001$) was calculated that explained 53% of the variance in driving impairment, with two significant predictors: perceived neurogenic symptoms (partial correlation = 0.53, $t = 4.6$, $P < 0.0001$) and

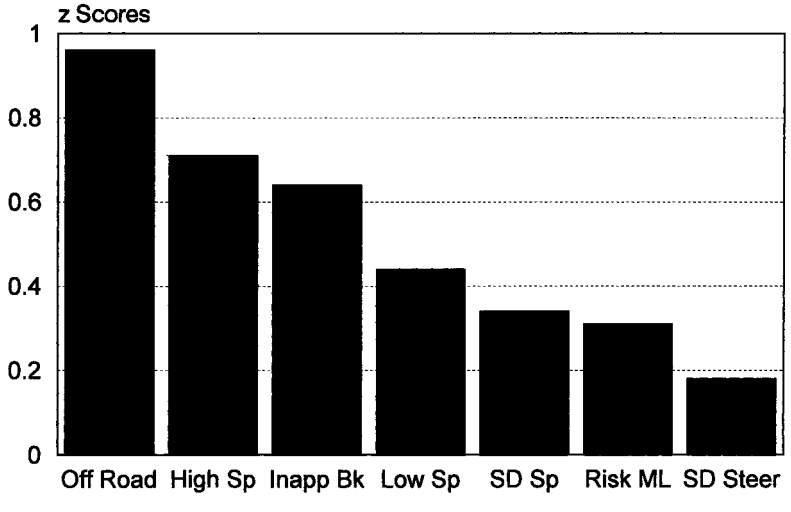

Figure 3—*Mean maximum* z *scores for the three levels for hypoglycemia. Bk, braking; Inapp, inappropriate; ML, midline; Sp, speed.*

Table 5—*Post hoc comparisons of different subgroups on the Composite Driving Impairment scores*

Comparison groups	Mean Composite Driving Impairment scores	*P*
Impaired versus normal hypoglycemia awareness	1.0 vs. 1.9	0.21
Recent history versus no history of severe hypoglycemia	1.3 vs. 1.7	0.61
Men versus women	1.4 vs. 1.6	0.82
Low BG in previous 48 h versus no recent low BG	1.9 vs. 1.2	0.45
≤2 vs. ≥3 insulin injections per day	1.2 vs. 1.8	0.50

increase in theta (partial correlation = 0.33, $t = 2.7$, $P < 0.01$). In other words, driving impairment was associated with more autonomic arousal and depression of the central nervous system at moderate hypoglycemia. However, at BG levels <2.8 mmol/l, driving impairment was not predicted by any of the measures.

Similar predictor variables were used to predict subject awareness of impaired driving *z* scores. Recognition of driving impairment was predicted ($R^2 = 38$, $F = 20.9$, $P < 0.001$) by neuroglycopenic symptoms (partial correlation = 0.55, $t = 4.4$, $P < 0.001$), high beta-wave activity (partial correlation = −0.28, $t = 2.3$, $P < 0.03$), and estimated BG (partial correlation = −0.25, $t = 2.1$, $P < 0.05$).

Finally, we used a discriminant analysis to differentiate subjects who either did or did not take corrective action (treated and/or stopped driving) on the basis of the EEG, neurogenic and neuroglycopenic symptoms, estimated BG level, need to treat, impaired driving ratings, and Composite Driving Impairment score. Four variables entered a significant discriminant model that correctly classified 92% of those who did take a corrective action and 72% of those who did not. Predictive variables, in order of significance (partial correlations), were as follows: perceived need to treat (0.42), estimated BG (−0.37), and low theta (−0.26) and high beta (0.15). Thus, subjects were more likely to treat themselves the more alert (high beta/low theta) and the more aware (greater detection of and perceived need to treat low BG) they were.

Post hoc analyses

We investigated whether certain subgroups were more at risk for hypoglycemia-induced impaired driving. Subjects with a history of repeated severe hypoglycemia (more than two events in the past 12 months) were contrasted with those having no recent severe hypoglycemia. Subjects were also dichotomized into those with normal or reduced hypoglycemia awareness, as defined by Clarke et al. (11), and compared. To assess sex differences, male subjects were compared with female subjects. To investigate whether recent experience with hypoglycemia related to hypoglycemia-impaired driving, subjects who reported experiencing a BG <3.8 mmol/l within the 48 h before testing were compared with those who reported no such recent events. Finally, we compared subjects who were taking one or two versus three or more (intensive therapy) insulin injections a day. As seen in Table 5, these variables were not related to hypoglycemia-induced driving impairments.

CONCLUSIONS — While we and others (5,6,28) have reported cognitive-motor impairments at relatively mild hypoglycemia (e.g., 3.6 mmol/l), the only study investigating driving performance (9) did not find impairments until BG reached 2.5 mmol/l. However, that investigation involved a relatively simple simulator, with relatively nondemanding driving scenarios that lasted only 5 min, during stepped hypoglycemia. Using a more sophisticated simulator and scenarios and progressive hypoglycemia, this study documented driving impairment at relatively mild hypoglycemia (4.0–3.4 mmol/l). Not only do these current findings parallel previously published neuropsychological deficits at similar BG levels, but driving impairment was confirmed by subjects' awareness of driving impairments. Driving impairments during mild to moderate hypoglycemia were accounted for by autonomic arousal, as defined by perceived neurogenic symptoms, and depression of the central nervous system, as defined by increased theta-wave activity.

While driving performance was impaired at mild hypoglycemia, as in previously published cognitive-motor test studies, the BG range at which driving was impaired and the exact driving parameters disrupted were quite idiosyncratic. This becomes obvious when contrasting the data presented in Table 4 and Fig. 3. Of the 21 possibilities in Table 4 (seven driving variables × three BG levels), only 5 demonstrated significant group effects. However, when considering a subject's worst performance at any hypoglycemic level, as in Fig. 3, we see that all of the driving performance variables were significantly affected at some point during hypoglycemia (all $P < 0.05$). Another illustration of idiosyncrasy is that of the 37 subjects, only 14 (38%) demonstrated an overall severe driving impairment relative to their euglycemic performance (>2 SDs). However, this 38% is a conservative estimate of those significantly impaired for three reasons. First, the methodology allowed any practice effect to optimize hypoglycemic driving. Second, the criterion of >2 SDs in Composite Driving Impairment was based on performance averaged across the entire 30 min of progressive hypoglycemia. Consequently, some subjects may have achieved significant driving impairments at lower BG levels without their overall average performance reaching the criteria of exceeding their euglycemic driving performance by the 98th percentile (2 SDs). Third, whether driving impairment is actually captured is dependent on the demand of the driving scenario. While neuroglycopenia may render a driver incapable of rapidly processing information and responding appropriately, unless such a driving demand is placed on the driver, then nothing bad would necessarily occur. This is clearly illustrated by patient reports describing driving experiences in which the impaired driver could not remember the drive and others had to intervene in some way but no accident occurred.

There appears to be a disconnect between awareness of driving impairment and corrective action. Only 11 of the subjects (30%) actually took corrective action. This disconnection is confirmed and clarified by the discriminant analysis. Corrective behavior was associated with both minimal neuroglycopenia (high beta and low theta) and awareness both of low BG and impaired driving. While discriminant analysis did not demonstrate that actual

driving impairment (Composite Driving Impairment score) contributed to whether subjects took corrective action, χ^2 did demonstrate that taking action was more likely to occur among those most impaired (>2 SD elevation in Composite Driving Impairment scores). Although significantly related to driving impairment, 43% (6 of 14) of the significantly impaired drivers never took corrective action. Treatment was only significantly more likely to occur during hypoglycemia at very low BG levels (<2.8 mmol/l), which was below the level at which driving impairments occurred.

This study demonstrates that hypoglycemia is a significant factor in impaired driving and that patients are generally aware of when their driving performance is deteriorating. However, these data also indicate that patients are not likely to treat their low BG while driving. In large part, this appears to be due to waiting too long before taking corrective action. In the current study, subjects waited to treat themselves until after their BG fell below 2.8 mmol/l. This is a BG level associated with the greatest elevation in theta-wave activity, which was negatively associated with self-treatment. The hesitation to treat low BG or stop driving when hypoglycemic was recently confirmed with field data in which subjects were asked whether or not they would drive based on what they thought their BG was but without knowing their actual BG (2). Subjects reported being willing to drive 45% of the time when their actual BG was between 2.2 and 2.8 mmol/l.

In general, this study suggests that patients should be encouraged to treat themselves immediately, whenever they think their BG is low or their driving is impaired, and not to wait until either they become too neuroglycopenic or their driving is too impaired. Furthermore, these data suggest that it would be prudent for drivers with type 1 diabetes to measure their BG before driving, not to start driving when their BG is 5–4 mmol/l without first treating their BG, and not to drive when their BG is <4 mmol/l. This study suggests that drivers should keep fast-acting glucose readily available, e.g., clipped to the visor, so that finding it is not an additional delay or barrier to self-treatment. However, because of the idiosyncrasies of these findings and the limitations of this study (small sample size, use of simulation), the direct relevance of these findings to actual driving risk is unclear. Additionally, because this and recent survey data do not indicate that diabetes has an increased driving risk (2,3), these findings cannot be implied to have direct relevance to driving privileges.

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