ORIGINAL ARTICLE

An integrated physiological and performance profile of professional tennis

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Br J Sports Med 2007;**41**:531–536. doi: 10.1136/bjsm.2006.031351

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Accepted 6 March 2007
Published Online First 1 May 2007

Objective: To describe the physiological responses to tournament tennis in relation to prevailing environmental conditions, match notation, and skills that underpin performance.
Design: 14 male professional tennis players (mean (SD) age, 21.4 (2.6) years; height, 183.0 (6.9) cm; body mass, 79.2 (6.4) kg) were studied while contesting international tennis tournaments. Environmental conditions, match notation, physiological (core temperature, hydration status, heart rate, blood variables), and performance indices (serve kinematics, serve velocity, error rates) were recorded.
Results: Hard and clay court tournaments elicited similar peak core temperature (38.9 (0.3) *v* 38.5 (0.6) ℃) and average heart rate (152 (15) *v* 146 (19) beats/min) but different body mass deficit (1.05 (0.49) *v* 0.32 (0.56)%, $p<0.05$). Average pre-match urine specific gravity was 1.022 (0.004). Time between points was longer during hard court matches (25.1 (4.3) *v* 17.2 (3.3) s, $p<0.05$). Qualitative analysis of first and second serves revealed inverse relations between the position of the tossing arm at ball release and the position of the ball toss and progressive match time (respectively, $r=-0.74$ and $r=-0.73$, $p<0.05$) and incurred body mass deficit ($r=0.73$ and $r=0.73$, $p<0.05$).
Conclusions: Participants began matches in a poor state of hydration, and experienced moderate thermoregulatory strain and dehydration during competition. These adverse physiological conditions may compromise performance and influence notational analyses.

Tennis performance is multifactorial, reflected by a sophisticated integration of physiological, biomechanical, psychological, and perceptual elements, all having considerable influence on the outcome of a match.[1] In competition, the integration of these performance facets is challenged by variable environmental conditions, playing surfaces, match durations, and playing strategies. The combination of these factors predisposes players to physiological strain that evolves either involuntarily (for example, hyperthermia, central fatigue)[2 3] or through player negligence (dehydration, hypoglycaemia).[4 5]

The consequences of homeostatic disruptions are often overt in elite tennis. However, a review of published reports showed that integrated physiological and performance analyses of professional tennis had not been attempted. Rather, simulated match and tournament conditions were the prevalent research approach.[5 6] Those who analysed match play generally applied a notational approach, recording rally duration, shots per rally, inter-point time, inter-serve time, and comparisons across different court surfaces.[7–9]

This investigation describes physiological responses to professional tournament tennis. The influence of physiology on match notation and performance variables (serve velocity, accuracy, serve kinematics, and error rates) was also examined. Both court surface and environmental conditions have a significant influence on physiological responses to match play and thus potentially on notational analyses and performance markers, and so must be considered when interpreting findings. It was hypothesised that during competition professional tennis players experience various types and degrees of physiological strain. A negative association between measures of physiological strain and performance was also proposed.

METHODS

Participants

Fourteen internationally ranked male tennis players participated in the investigation. Their average ranking was 512, range 125 to 882); mean (SD) age, 21.4 (2.6) years; height, 183.0 (6.9) cm; and body mass, 79.2 (6.4) kg. Participants trained on average for 32 hours a week during out-of-competition phases and had at least five years of national level tournament experience. Participants received explicit details of the experimental protocol before voluntarily consenting. Between tournaments a battery of physical tests was carried out and maximum heart rate was determined.

The study was reviewed and approved by the Australian Institute of Sport and the University of Ballarat ethics committees.

Study design

Tournament details

The investigation was carried out during two hard court tournaments and one clay court tournament on the 2003/2004 Australian summer and autumn tennis circuits (37 datasets were produced from 33 matches). Matches in all tournaments were best of three sets, and were contested between 0900 and 1700 hours. Matches were played outdoors and all facilities and equipment were defined according to the International Tennis Federation.[10]

Pre-match determinations

Participants carried out their routine game preparation with a few minor modifications. They arrived to the courts with their upon-waking urine sample, having previously ingested (at least three hours before start of play) a core temperature measurement capsule. Immediately before starting each match, participants emptied their bladders before being weighed nude. Subsequently a Polar Team System (Polar Electro Oy, Finland) heart rate chest strap was fitted, and baseline physiological

Abbreviations: RH, relative humidity; T_C, core body temperature; T_{WB}, wet bulb temperature; U_{sg}, urine specific gravity measurements conducted. Nude body mass was measured on electronic scales (UC-300 Precision Health Scale, and Mercury Pty Ltd, South Australia). Core body temperature (T_C) was measured by short range telemetry from the single use capsule residing in the gastrointestinal tract to a data logger, BCTM3 (Fitsense Technology, USA). Urine specific gravity (U_{sg}) was measured from the upon-waking sample, using either a Bayer Multistix test strip (8SG, Bayer Diagnostics Manufacturing, South Wales) or a digital urine SG refractometer (UG-1, Atago Co, Tokyo, Japan). Capillary blood samples, including blood glucose (measured using a HemoCue (Angelholm, Sweden)), creatine kinase, creatinine, urea, and uric acid were analysed using a Reflotron (Roche Diagnostics, Indianapolis, Indiana, USA) or a Hitachi 911 automatic analyser (Hitachi Ltd, Tokyo, Japan). Reduced blood glucose and raised creatine kinase, creatinine, urea, and uric acid have been reported in athletes carrying out high volume training.[11] The total weights of the players' food and fluids carried to the court were ascertained, using digital electronic kitchen scales (Portion Power, InterTAN Australia).

During match play

During game and set breaks, T_C and fluid consumption were monitored. Water and carbohydrate loaded (6%) sports drinks were available for participants. Serve velocity, serve kinematics, match notation, and environmental conditions (ambient temperature, court temperature, relative humidity (RH), wet bulb temperature (T_{WB}), and wind speed) were recorded. Matches were filmed from one end of the court, using a digital video camera (Sony DCR-VX2000E PAL, Japan). The footage was used to conduct the retrospective notational analysis using customised software (TenTimer V1.1, AIS, Canberra). A second digital video camera (Sony DCR-TRV950E, Japan) filmed the anterior plane of the participant executing the serve. The footage of individual serves of each game was qualitatively analysed by two elite coaches using a standardised checklist, producing a consistency percentage. The checklist assessed whole body technical components, including smoothness of action, hip and shoulder rotation (separation angle), sequence of body segments (kinetic chain), knee flexion and extension, height of the tossing arm at ball release, position of the ball toss, and the landing distance inside the court after racquet ball impact. First and second serve velocity was measured using a radar gun (Stalker Professional Sports Radar, Radar Sales, Plymouth, Minnesota, USA) placed 5 m behind the server, aligned with ball–racquet contact. Environmental conditions were monitored at five minute intervals using a digital weather tracker (Kestrel 4000, Nielsen-Kellerman, Australia) placed 1 m above the ground on the side court fencing. Court temperature was measured using a digital temperature analyser (Testo 610, Testo Sense, Victoria, Australia) placed on the court surface 50 cm inside the court fencing. Both apparatuses were positioned so that they were unimpeded by shade.

Table 1 Environmental conditions during the hard and clay court tennis tournaments

	Hard court		Clay court	
	Mean (SD)	Min–max	Mean (SD)	Min–max
Temperature (°C)	32.0 (4.5)*	24.9–43.1	25.4 (3.8)	19.6–33.8
RH (%)	38 (14)	12–62	32 (5)	21–43
Wind speed ($m \cdot s^{-1}$)	1.2 (1.7)	0.0–10.8	1.2 (1.1)	0.0–5.3
T_{WB} (°C)	21.7 (1.9)*	17.1–26.5	16.1 (2.6)	11.9–23.7
Court temperature (°C)	40.4 (5.3)*	31.4–51.5	34.1 (4.3)	24.6–42.7

Values (n = 6) presented are mean (SD), minimum and maximum.
*Significant difference between the hard and clay court tournaments ($p<0.05$).
RH, relative humidity; T_{WB}, wet bulb temperature.

Post-match

Participants returned immediately to the testing area for assessment of nude body mass (towelled dry) and capillary blood samples (creatine kinase, creatinine, and blood glucose). Final weighing of food and fluid consumed was carried out. This ensured that all possible influences on body mass change were accounted for.

Statistical analysis

Data from the two hard court tournaments were pooled, whereas the single clay court tournament data are presented individually. Six participants competed in tournaments on both surfaces. Data from only those six participants were used for statistical analyses. Data were analysed using SPSS version 11.0 (SPSS Inc, USA). Standard descriptive statistics characterised the 14 participants. As a result of significant differences in environmental conditions, comparisons across the different court surfaces were not warranted. Instead, the purpose was to present physiological profiles of tournament tennis and in doing so, infer a role of physiological perturbation on match outcomes. However, in some cases paired *t* tests compared environmental conditions, notational analyses, and physiological responses between matches played on different court surfaces and pre- versus post-match responses. Where data expressed significant non-normality, non-parametric statistics were used to examine statistical significance (Wilcoxon signed rank test). A correlation matrix was used to identify relations between physiological responses, performance variables, and match notation over the duration of a match. Correlations were conducted using only measurements up to the duration of the shortest match from pooled data of hard and clay court matches. Statistical significance was identified at a probability (p) value <0.05.

RESULTS

Environmental conditions

Ambient temperature ($t = -2.988$, $p = 0.031$), T_{WB} ($t = -3.59$, $p = 0.016$), and court temperature ($t = -2.731$, $p = 0.041$) were significantly higher during the hard court tournaments than during the clay court tournament (table 1).

Physiological responses

Physiological responses to hard court and clay court tournaments are presented in table 2. The estimated playing intensity averaged 78% and 75% of maximum heart rate for hard and clay court matches, respectively. Post-match body mass deficits were significantly greater during hard court matches (hard courts *v* clay courts: 1.05 (0.49)% *v* 0.32 (0.56)%, $z = -2.201$, $p<0.05$). Only eccrine and urinary/faecal losses were considered in the calculation of changes in body mass. Pooling data from both hard and clay court tournaments, pre- versus post-match analysis of blood variables showed that blood glucose ($t = -3.202$, $p = 0.008$), creatine kinase ($t = 4.835$, $p = 0.005$) and creatinine (Wilcoxon $z = -3.062$, $p = 0.002$) were significantly higher after the match.

Performance characteristics

Quantitative

Match performance variables are presented in table 3. No significant differences were identified between court surfaces and no correlations were revealed with physiological manifestations. First serve velocity negatively correlated with court

Table 2 Physiological responses to matches played on hard and clay courts

	Hard court		Clay court	
	Mean (SD)	Min–max	Mean (SD)	Min–max
Peak core temperature (℃)	38.9 (0.3)	38.6–39.3	38.5 (0.6)	37.9–39.5
Sweat rate (kg.h^{-1})	2.04 (0.44)	1.53–2.77	1.51 (0.32)	1.08–1.86
Body mass deficit (%)	1.05 (0.49)*	0.39–1.59	0.32 (0.56)	−0.47–0.95
Fluid consumed vs fluid lost (%)	77 (12)	63–90	89 (26)	68–133
Average heart rate (beats/min)	152 (15)	137–173	146 (19)	130–167
Pre-match BGL (mmol·l^{-1})	5.2 (0.6)	4.5–5.7	6.4 (2.4)	3.8–10.4
Post-match BGL (mmol·l^{-1})	6.7 (2.2)	3.6–8.6	8.4 (1.9)	6.3–11.1
Pre-match CK (µmol·l^{-1})	–	–	255 (73)	134–344
Post-match CK (µmol·l^{-1})	–	–	312 (87)	161–414
Pre-match creatinine (µmol·l^{-1})	70 (7)	60–79	81 (6)	71–89
Post-match creatinine (µmol·l^{-1})	87 (14)	70–107	96 (8)	90–113
Pre-match urea (mmol·l^{-1})	5.6 (1.0)	4.4–7.0	6.3 (0.5)	5.4–6.9
Pre-match uric acid (µmol·l^{-1})	321 (89)	176–385	342 (43)	298–412
Urine specific gravity	1.023 (0.004)	1.015–1.025	1.021 (0.004)	1.017–1.028

Values (n = 6) presented are mean (SD), minimum and maximum. Equipment failure hampered the collection of creatine kinase during the hard court tournaments.
*Significant difference between the hard and clay court tournaments ($p<0.05$).
BGL, blood glucose; CK, creatine kinase.

temperature ($r = -0.772$, $p<0.05$). Second serve velocity correlated with RH ($r = 0.708$, $p<0.05$) and negatively with ambient temperature ($r = -0.739$, $p<0.05$) and T_{WB} ($r = -0.734$, $p<0.05$).

Qualitative

Longitudinal assessment of serve kinematics revealed correlations (listed below under the headers "*First serve*" and "*Second serve*") between technical inconsistencies and a several match variables, using pooled data from hard and clay court matches.

First serve

Consistency in the height of the tossing arm at ball release inversely correlated with both progressive match time ($r = -0.741$, $p<0.05$) and body mass deficit ($r = 0.730$, $p<0.05$).

Second serve

Consistency in position and height of the ball toss inversely correlated with both progressive match time ($r = -0.729$, $p<0.05$) and body mass deficit ($r = 0.725$, $p<0.05$).

Match notation

Match statistics for hard and clay tournaments are presented in table 4. Environmental conditions appeared to influence player recovery time between points, which was significantly longer during hard court matches (hard *v* clay: 25.1 (4.3) s *v* 17.2 (3.3) s, $t = -6.886$, $p<0.01$). No other match statistic differed significantly between court surfaces. Increasing T_C was the only physiological strain index that displayed a relation with match notation: time between games ($r = 0.908$, $p<0.01$), time between points ($r = 0.815$, $p<0.05$), shots per rally ($r = 0.728$, $p<0.05$), and rally duration ($r = 0.794$, $p<0.05$).

Table 3 Quantitative performance indices of men's professional tennis matches played on hard and clay courts

	Hard court Mean (SD)	Clay court Mean (SD)
First serve velocity (kph)	178 (9) (n = 445)	172 (14) (n = 375)
Second serve velocity (kph)	135 (10) (n = 199)	134 (12) (n = 147)
First serve accuracy (%)	56 (24)	55 (24)
Points won on first serve (%)	72 (33)	76 (25)
Points won on second serve (%)	63 (34)	61 (35)
Unforced errors (%)	24 (13)	24 (17)

Of the two players contesting each match, values (mean (SD)) represent those of only the player participating in the investigation (n = 6). Values in parentheses (n) represent the number of data from which mean and SD are derived.

DISCUSSION

Physiological profile and potential performance implications

This investigation showed that professional tennis players competed while experiencing moderate thermoregulatory strain and hypohydration. Alongside these findings were mild increases in cardiovascular demand and indicators of muscle damage. Collectively, the effects of hot and humid ambient conditions, repeated ballistic actions, and intermittent exercise over a prolonged period are predisposing factors to homeostatic disruption and ultimately to performance impairment. Specifically, core temperatures approaching hyperthermia levels (exceeding 38.5℃) were common to both tournaments, irrespective of environmental conditions. As a result of the onset of exercise and increased metabolic heat production, this response generally occurred shortly after the start of the match, influencing several match notation variables and predisposing players to premature fatigue,[12] performance decrements,[13] and heat illness.[14] In this instance, performance implications were technical modifications of the service motion; however, the effects on outcome measures are not clear. It is shown that players experience various facets of physiological strain for substantial periods of play. This generates promise for future investigations of strategies to reduce physiological compromise.

Match preparation and hydration status

Analysis of pre-match hydration status reaffirmed the poor hydration practices of tennis players.[15] Urine specific gravity below 1.020 is recommended for optimum pre-exercise hydration, particularly for prolonged activities in hot and humid conditions.[16] Pre-exercise hyperhydration ascribes thermoregulatory benefits, such as earlier onset of sweating and mitigated increases in core temperature, relative to euhydration.[17] In the current investigation some athletes returned upon-waking U_{sg} values as high as 1.030, showing the need to drink more in preparation for and recovery from matches. Whether players'

Table 4 Notational analyses of men's professional tennis matches played on hard and clay courts

	Hard court		Clay court	
	Mean (SD)	Min–max	Mean (SD)	Min–max
Match duration (min)	119 (36)	84–171	79 (13)	61–101
Rally length (s)	6.7 (2.2)	3.1–15.0	7.5 (3.0)	2.8–17.9
Shots per rally	4.7 (1.4)	2.4–8.4	4.5 (2.0)	2.3–11.8
Direction changes per rally	2.5 (0.9)	1.0–4.6	2.4 (1.3)	1.2–8.4
Time between games (s)	59.9 (18.1)	23.9–108.6	50.0 (18.5)	8.0–117.5
Time between points (s)	25.1 (4.3)**	16.7–34.4	17.2 (3.3)	10.2–27.5
Time between serves (s)	11.7 (3.2)	5.2–22.1	10.6 (2.5)	7.6–24.4

Values (n = 6) presented are mean (SD), minimum, and maximum.
**Significant difference ($p<0.01$) between the hard and clay court tournaments.

hydration status changed between waking and the start of play was not, however, assessed.

Hydration behaviours during match play under hot and humid conditions further emphasised the need for player education. During 13 of the 17 hard court matches studied participants incurred greater than 1% body mass deficit, consuming only 66 (18)% (2329 (1104) ml) of total fluid loss. On three occasions body mass deficits greater than 2.0% were reported. Comparatively, during only one of the 20 clay court matches studied (played in mild ambient conditions) did participants incur equivalent body mass deficits, consuming 97 (26)% (1908 (694) ml) of total fluid loss. Tennis matches are often played under thermally challenging conditions which would augment the above responses, placing players at risk of performance deterioration and compromised health. There is extensive research demonstrating compromised cognitive[18] and motor/physical[19] performance under states of hypohydration. Body mass deficits observed in this investigation are comparable to previous tennis research[20 21] and are easily offset through adherence to prescriptive hydration regimens.

Substrate availability and hypoglycaemia as a fatigue mechanism

In agreement with previous investigations of moderate[22] and prolonged tennis play,[23] the current investigation showed that hypoglycaemia does not manifest during match play. Participants displayed relatively high post-match blood glucose concentrations which are comparable to those in studies of simulated match play.[3 24] It appears that ingestion of carbohydrate beverages is sufficient to maintain blood glucose concentration to match the increased uptake of glucose by active musculature. However, the moderate duration matches studied in the current investigation may not have been sufficient to challenge and lower blood glucose levels. Significant rises in core body temperature were recorded during both tournaments which would increase carbohydrate oxidation.[25] Further research of prolonged tennis match play, equivalent to five-set matches, is required before hypoglycaemia can be ruled out as a mechanism inducing performance deterioration.

Match intensity

Average heart rate values support the playing intensity estimates of previous research.[6 24] Maximum heart rate attained during play on hard and clay courts, respectively, equated to 93% and 94% of maximum heart rate previously obtained when participants undertook a 20 m shuttle run test. These observations, in addition to confirming the high intensity intermittent nature of tennis, confirm that cardiovascular strain also presents a physiological challenge to sustained performance during match play. Despite no measurement of recovery rate in this study, it appears that the time between points and games is sufficient for players to recover from the intermittent high intensity periods of play, nullifying the previously reported dramatic effects of cardiovascular duress on tennis skill performance.[26]

Muscle damage associated with match play

Creatine kinase is an enzyme important for muscle energy production, but its increase in the circulation post-exercise is also indicative of muscle damage.[27] In the current study, post-match creatine kinase increased mildly but significantly relative to pre-match values. This response, which could be attributed to changes in plasma volume, occurred despite the players being conditioned to the ballistic movements (disruptive stimulus) of tennis, which is said to reduce muscle trauma.[28] It is hypothesised that greater tissue damage would accumulate during a prolonged match and over the course of a tournament. This response could increase a players' susceptibility to performance impairment and acute or chronic injuries. These observations emphasise the need for players to employ effective recovery strategies between matches.

Match notation

The standard match statistics of the current investigation are comparable to those of previous researchers.[7–9] O'Donoghue and colleagues reported average rally lengths 6.3 (1.8) s and 7.7 (1.7) s, inter-point times of 18.7 (1.9) s and 19.5 (2.1) s, and inter-serve times of 9.3 (1.5) s and 9.2 (1.3) s for men's Grand Slam tournament matches played at the Australian Open (hard courts) and the French Open (clay courts), respectively. One exception was the length of inter-point time on different court surfaces. O'Donoghue and Ingram[8] reported longer recovery times during clay court matches and reasoned this was because of the longer rally lengths, whereas players in the current investigation required longer recovery times during the hard court matches. The different findings are likely to be related to the different environmental conditions. Additionally, this investigation revealed that increasing T_C also influenced match notation, highlighting the need to consider the many variables that determine match notation. Overall, the similarity in match statistical data between Grand Slam and entry level professional tennis tournaments adds merit to inferences applied from the overall findings of this investigation to elite tennis.

Correlations over time between physiological responses and performance

This is the first investigation identified in tennis that has attempted to correlate the increasing physiological demand of match play with skills that underscore performance. The

What is already known on this topic

- Tennis is an intermittent high intensity sport, played over a long duration. Anecdotally, fatigue manifests during match play and impairs performance. In the professional tennis domain notational analyses are the prominent research endeavour, with physiological studies performed in training or simulated competition environments or with different athlete populations.

What this study adds

- An integrated profile of physiology, match notation, and performance during professional tournament tennis is provided. Specific physiological perturbations are identified and linked to deterioration of process skills that underlie performance.

qualitative analysis of first and second serves indicated that as matches progressed and adverse physiological conditions developed (for example, increased heart rate, body mass deficits, heat strain), elements of the service action were negatively affected. This finding is consistent with other investigations of elite sports[29] and is suggestive of a relation between physiological strain and diminished technical skill performance. Specifically, consistency in the height of the arm at ball release, and the position and height of the ball toss were the most overt technical inconsistencies. General fatigue, possibly modulated through hyperthermia or hypohydration, may also explain performance deterioration, but this possibility could not be confirmed nor discarded on the basis of the available data.

While it could be expected that modifications to coordination and timing of the movement pattern would compromise the outcome of the stroke,[30] this was not realised under match conditions as there were no prevailing reductions in serve velocity and accuracy. These findings are in agreement with those of Royal *et al*,[29] who observed altered technical proficiency but unchanged shooting velocity and accuracy with increasing levels of physiological strain in water polo players. This suggests either that the kinematic components that demonstrated inconsistency with physiological strain are not integral to sustained stroke velocity and accuracy, or that highly skilled athletes are able to maintain performance proficiency under duress.

CONCLUSIONS

This investigation provides a comprehensive profile of entry level professional tennis (three-set matches), where match notation reflected that of elite tournaments. Simultaneous measurement of performance and physiological variables infers implications of physiological status on match outcomes. While not directly measured in this investigation, it is proposed that standardised assessment of performance variables in a controlled setting would identify skill deterioration associated with physiological strain. Inadequate pre-match hydration, body fluid deficits incurred during play, heat strain, and early signs of acute muscle damage stand as the dominant adverse responses. It is envisaged that the magnitude of these responses would increase during Grand Slam tournaments (five-set matches). In some instances stroke kinematics were negatively impacted by physiological stress warranting a more detailed examination of this relation.

ACKNOWLEDGEMENTS

We thank Dr Alan Pearce and the two elite coaches from Tennis Australia for their assistance during the data collection phase, and the Australian Institute of Sport, Tennis Australia and the University of Ballarat who collaboratively funded the project.

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COMMENTARY

The physiological demands of tennis are difficult to analyse, because tennis is a multifaceted sport with a stop-and-start nature, played on different court surfaces under a variety of environmental conditions. The authors have done a good job, monitoring a multiplicity of parameters simultaneously, in order to describe the physiological responses to professional tennis. One of the most interesting findings of the study is that notational analysis is not only influenced by court surface, but also by thermoregulatory strain, which may have important implications for performance.

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Jenny McConnell is a physiotherapist working in private practice in Sydney, Australia. She has a Bachelor of Applied Science (physiotherapy), Graduate diploma in Manipulative Therapy and Master's degree in Biomedical Engineering. Jenny has been involved in research into patellofemoral, shoulder and lumbar spine problems. She has published widely in these areas and has lectured extensively on the management of chronic musculoskeletal problems—patellofemoral, shoulder and spine. She has a visiting senior fellow position at Melbourne University. Jenny is currently on the editorial board of the *Clinical Journal of Sport Medicine* and *Manual Therapy* as well as the *British Journal of Sports Medicine*.

Figure 1 Jenny McConnell.