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Rates of Concussion Are Lower in National Football League Games Played at Higher Altitudes

While concussions occur in nearly every sport and level of competition, the greatest frequency occurs in collision and contact sports such as football, lacrosse, hockey, rugby, soccer, and basketball.[16,22,27] Specifically with regard to football, attempts at player-safety improvements for concussion prevention date back to the implementation of helmets by the National Football League (NFL) in 1943 and have continued virtually every year in the form of both rule changes and equipment modifications.[32] Although scrutiny of sport-related concussion has only recently come to the public forefront, sustaining 1 or more of these concussive injuries presents a danger that has been a concern of the NFL for decades.[6]

STUDY DESIGN: Retrospective epidemiologic investigation.

OBJECTIVE: To investigate the relationship between altitude and concussion rate in the National Football League (NFL). Because of the physiologic responses that occur during acclimatization to altitude, it was hypothesized that games played on fields at a higher altitude would have reduced concussion rates compared to games played on fields at a lower altitude.

BACKGROUND: Recent research indicates that the elevation above sea level at which football games are played may be associated with the likelihood of a concussion in high school football athletes.

METHODS: Data on incident concussions and athlete exposures for the first 16 weeks of the NFL 2012 and 2013 regular seasons were obtained from publicly available web-based sources and used to calculate competition concussion rates for each NFL stadium. Concussion rates were analyzed in relation to game elevation.

RESULTS: During the first 16 weeks of the 2012 and 2013 NFL regular seasons, 300 concussions, involving 284 players, were reported (64.3 primary cases per 10 000 game exposures). The odds of a concussion were 30% lower when playing at a higher elevation (equal to or greater than 644 ft [196.3 m] above sea level) compared to a lower elevation (odds ratio = 0.70; 95% confidence interval: 0.53, 0.94). A multivariable generalized linear model controlling for season, week, and clustering of team at home and away confirmed these results, showing that the odds of at least 1 concussion were reduced by 32% in games played at higher elevation.

CONCLUSION: The results of this epidemiological investigation indicate that increased altitude was associated with a reduction in the odds of a sport-related concussion in NFL athletes. The reported relationship of concussion incidence and field elevation should be further investigated, and, if verified, further work will be needed to understand why that relationship exists.

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With increased awareness of the rate of concussion injury and the potential detrimental long-term effects, the NFL has made efforts to identify the health consequences of repeated blows to the head while concurrently seeking to implement strategies that better protect the athletes from these injuries. In 2009, the league took a more aggressive stance on concussive events through the implementation of stricter guidelines for activities following postconcussion assessments. The postconcussion guidelines were revised and mandated that a player should not return to play if he exhibited any residual concussion symptoms (eg, loss of memory, headache, or dizziness) at rest

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or during exertion. This was a significant change from prior guidelines, which declared that players should not return to play on the same day only if they had lost consciousness at the time of injury.[4] In 2010, the NFL continued its "mitigation by education effort" through the distribution of educational posters and brochures that informed all teams of the detrimental effects of concussions and repeated brain injuries. The NFL expanded this effort in 2011 with the implementation of a protocol for sideline assessments of athletes suspected to have sustained a concussion injury.[25] From 2011 through the 2013 season, additional rule changes that aimed to protect players' safety were implemented. These amendments included shortening the distance between the opposing players at kick-off, which was intended to decrease the number of potentially dangerous collisions during run-backs,[26] and a ban on the initiation of contact with the crown of the helmet.[30] At the start of this season, the NFL bolstered efforts to increase identification of players with a potential concussion by updating the evaluation protocol to specifically include increased vigilance and more comprehensive evaluation by licensed professionals. Mandates now include a consultation for any player suspected of having a concussion by a board-certified neurologist unaffiliated with the player's team and the presence of a certified athletic trainer to act as a "spotter" in the press box at all games to help identify injured players.

The heightened concerns led by the NFL and the general population have resulted in the introduction of numerous devices[7,14] and dietary supplements[35] purported to protect athletes from concussion. Unfortunately, no studies have yet revealed a reduction in concussion incidence or mitigation of symptoms as a result of these new approaches.[7,9] The most common attempted strategy for prevention of concussion has been modifications to helmets that include innovations in design, padding, mouth guards, and product materials.[9,13] A major issue with many of these helmet modifications is that such technologies often increase the mass and/or size of the helmet, which can increase the potential for additional harm to the neck, due to an increase in leverage forces applied to the head. Current regulatory attempts at primary concussion prevention also remain focused on rule changes and protective gear, but these attempts may be myopic. Despite aggressive enforcement of helmet and protective-padding use, epidemiological and laboratory studies have not shown significant reductions in concussion incidence rates or the extent of concussive injury to the brain.[17] One hypothesis is that such devices and equipment do little to nothing to prevent or mitigate the rapid acceleration and deceleration of the brain and related fluids inside the rigid cranium.

Many species in the animal kingdom, including head-ramming sheep[12] and woodpeckers, routinely tolerate collisional impacts to the cranium with much greater forces than humans can tolerate. They do so through what is speculated to be a modulation of intracranial volume and pressure. For perspective, a typical brain impact that results from a collision at the high school football level can be measured at 25 to 50 *g*,[8] and motor vehicle accidents typically impart 50 to 100 *g*. In comparison, head-ramming sheep tolerate 500-*g* impacts, and woodpeckers sustain 1200-*g* impacts approximately 12 000 times a day, both species apparently suffering little to no harm. New research may benefit from a focus on whether the presumed hydrodynamics of the head-ramming sheep (carbon dioxide–mediated response to altitude) or the woodpecker (self-altered jugular outflow) can be mimicked to optimize brain compliance (or create a "tighter fit") inside the cranium and reduce the effects of concussive impacts.

Based on the science of fluid dynamics, slosh refers to the movement of liquid inside containers that are also typically undergoing motion.[24] When the head is exposed to rapid acceleration/deceleration, the brain may be at risk for slosh-induced injury. This occurs as tissues of differing densities (ie, blood, spinal fluid, brain, and skull) decelerate at different rates, thereby creating shear and cavitation (vapor-bubble creation and implosion). Preventing brain slosh during sport may be an important consideration in the reduction of concussion injury.[28,33]

The central hypothesis being explored relative to concussion prevention is that mild increases in intracranial volume induce a tighter fit of the brain inside the cranium and thus reduce slosh and inertial cavitation within the brain during concussive blows.[18,21,28,33,39] At present, there is no known approach that allows for the manipulation of intracranial volume or compliance in the human skull; therefore, the benefits of such an approach to protect the brain of humans are yet unknown. While helmet design was developed for, and is effective in, the prevention of skull fractures and lacerations, it does not afford protection against forces inside the cranium. There is, however, a potential natural physiological response that provides an opportunity to test hypotheses related to the concept that increased altitude results in an increase in hypoxic vasogenic edema[38] and may result in an effect similar, though less pronounced, to the mechanisms that have evolved to protect the brains of head-ramming sheep and woodpeckers.

A recently published epidemiological investigation of high school football evaluated nearly 6000 reported concussions over 7 years, categorized by topographical elevation of game location, ranging from 7 to 6903 ft (2.1-2104.0 m) above sea level. The data demonstrated an increased concussion rate (1.28; 95% confidence interval [CI]: 1.18, 1.37) at altitudes below the median-based 644 ft (196.3 m) cut value employed in the investigation.[29] Based on that prior investigation, the hypothesis of the current investigation was that NFL games played at higher altitudes would result in a reduced concussion rate compared to those played at a lower altitude.

METHODS

Participants

All players on active rosters for every NFL regular-season game (weeks 1-16) during the 2012 and 2013 seasons were monitored for concussion incidence. Because teams that do not make the playoffs are not required to report injuries following week 17 of the regular season, there was incomplete reporting for the final week of each season. Therefore, data from week 17 of the 2012 and 2013 seasons were not included in the analysis. All game exposures were tallied (46 players per active roster per team per game), resulting in 22 080 total competition exposures per year for the concussion incidence denominator and a total of 480 individual team game exposures per year. Approximately 30% of the games were played at or above a predefined threshold for higher altitude (644 ft [196.3 m] or greater above sea level), which provided 80% power, with type 1 error of .05 using a 2-sided test, to detect an odds ratio of 0.58 in the percentage of games with at least 1 concussion played in higher versus lower altitude for 2 seasons.

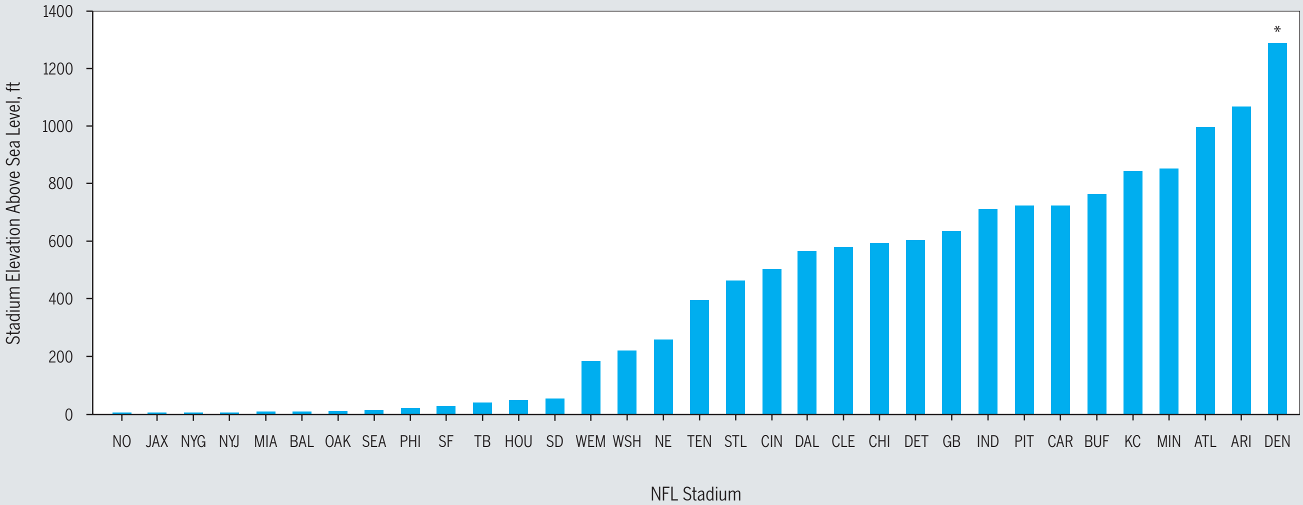
Procedures

Elevation Calculations The approximate elevation above sea level (in feet) of all venues for NFL games played in the 2012 and 2013 regular seasons (weeks 1-16) was obtained utilizing web-based resources. City location and stadium venue for all regular-season games that were played between weeks 1 and 16 of the 2012 and 2013 seasons were collected via ESPN's NFL schedule-grid website (http://espn.go.com/nfl/schedulegrid). After documenting each regular-season game venue for the 2012 and 2013 seasons, altitudes and coordinates for the stadiums were approximated using a web-based elevation-approximation map (http://www.daftlogic.com/sandbox-google-maps-find-altitude.htm), which measures elevation based on coordinates relative to sea level. The landmark chosen to measure elevation for each venue was approximately the center of the playing field of each stadium. The elevation of each stadium was then recorded and assigned to each stadium code. The stadiums were divided into 2 categories: lower elevation (less than 644 ft [196.3 m]) and higher elevation (greater than or equal to 644 ft [196.3 m]), based on the previous altitude investigation in nationwide high school football.[29] Of all 33 venues, including Wembley Stadium in England and those venues that hosted regular-season NFL games during the 2012 and 2013 seasons, 9 were considered to be located at a higher elevation, and the remaining venues below 644 ft above sea level were categorized as lower-elevation venues (**FIGURE**).

Concussion Data Collection Concussion data were collected utilizing the PBS Frontline Concussion Watch web-based resource (http://www.pbs.org/wgbh/pages/frontline/concussion-watch/#).[11] Data were collected for both the 2012 and 2013 competitive regular NFL seasons (excluding week 17). A concussion was tallied for this analysis if the PBS Frontline site designated the injury type for a player as "concussion." Additionally, the concussion was only included in the analyses if it occurred during a regular-season game; therefore, concussions sustained during practice were not included. The data available on the PBS Frontline Concussion Watch included the player's name, team, position at time of concussion, week of injury, and games missed. The PBS Frontline Concussion Watch aggregates and cross-references multiple sources of information, including Football Outsiders, NFL injury reports, and team websites,[11] which makes it the most accurate source of information available for these data. The teams' opponents were matched with the week of the injury and the ESPN NFL website schedule. Location of injury was determined by matching the week of injury indicated on the PBS Frontline Concussion Watch website with the ESPN NFL website schedule grid. A secondary goal was to examine the mechanism of injury for each concussion event, as these data were also available via the PBS Frontline Concussion Watch website and other related sources. If a player sustained multiple concussions, only the first concussion in the season was utilized in the initial player analysis.

Data Analysis

The initial approach for data analysis was a simple player-level examination of the rate of concussion for total exposure at the dichotomized altitude level, with lower elevation as less than 644 ft (196.3 m) and higher elevation as greater than or equal to 644 ft (196.3 m). If a player sustained multiple concussions, only the first concussion in the season was utilized in this analysis (n = 284) and second concussions (n = 16) were excluded. Concussion rates were compared between the altitude groups using a chi-square test with a Yates correction. Next, a multivariable generalized linear model was used to examine the association between game field elevation and any concussion event by team per game. All reported concussions were included and a team concussion event was defined as at least 1 concussion in any team member for that game. Using this approach, we were able to account for season, week within season, home game, and correlation within team when examining the effect of altitude. A generalized estimating equations approach was used to account for multiple games, at home and away, per team. This information was included as a repeated measure in the model, and compound symmetry was assumed for the underlying covariance structure. Examination of elevation as a dichotomy, using 644 ft above sea level as the cut point, was the first independent variable of interest. Secondarily, we examined the rates using quartile cuts of the altitude levels for the stadiums. We did not look at altitude as a continuum, due to the skewed distribution of altitude, and, although log and Box-Cox transformations of the variables were examined, the resulting distributions were still not considered ap-



Abbreviation	City	Stadium	Team
ARI	Glendale, AZ	University of Phoenix Stadium	Cardinals
ATL	Atlanta, GA	Georgia Dome	Falcons
BAL	Baltimore, MD	M&T Bank Stadium	Ravens
BUF	Orchard Park, NY	Ralph Wilson Stadium	Bills
CAR	Charlotte, NC	Bank of America Stadium	Panthers
CHI	Chicago, IL	Soldier Field	Bears
CIN	Cincinnati, OH	Paul Brown Stadium	Bengals
CLE	Cleveland, OH	FirstEnergy Stadium	Browns
DAL	Arlington, TX	AT&T Stadium	Cowboys
DEN	Denver, CO	Sports Authority Field at Mile High	Broncos
DET	Detroit, MI	Ford Field	Lions
GB	Green Bay, WI	Lambeau Field	Packers
HOU	Houston, TX	Reliant Stadium	Texans
IND	Indianapolis, IN	Lucas Oil Stadium	Colts
JAX	Jacksonville, FL	EverBank Field	Jaguars
KC	Kansas City, MO	Arrowhead Stadium	Chiefs
MIA	Miami, FL	Sun Life Stadium	Dolphins
MIN	Minneapolis, MN	Hubert H. Humphrey Metrodome	Vikings
NE	Foxborough, MA	Gillette Stadium	Patriots
NO	New Orleans, LA	Mercedes-Benz Superdome	Saints
NYG	East Rutherford, NJ	MetLife Stadium	Giants
NYJ	East Rutherford, NJ	MetLife Stadium	Jets
OAK	Oakland, CA	O.co Coliseum	Raiders
PHI	Philadelphia, PA	Lincoln Financial Field	Eagles
PIT	Pittsburgh, PA	Heinz Field	Steelers
SD	San Diego, CA	Qualcomm Stadium	Chargers
SEA	Seattle, WA	CenturyLink Field	Seahawks
SF	San Francisco, CA	Candlestick Park	49ers
STL	St Louis, MO	Edward Jones Dome	Rams
TB	Tampa, FL	Raymond James Stadium	Buccaneers
TEN	Nashville, TN	LP Field	Titans
WEM	London, UK	Wembley Stadium	NA
WSH	Landover, MD	FedEx Field	Redskins

FIGURE. The altitude of each stadium approximated at the 50 yard line. Abbreviation: NA, not applicable. *Actual elevation of Denver is 5192 ft above sea level.

TABLE 1 Odds Ratio of Concussive Event, Based on the Altitude of Football Stadiums

	Altitude, ft*	Odds Ratio†	*P* Value
Dichotomous analysis‡			
0 to 643 ft	52 (11, 483), n = 24	Reference	...
644 ft or greater	842 (725, 995), n = 9	0.68 (0.47, 0.99)	.04
Quartile analysis			
0 to 19 ft	9 (6, 11), n = 9	Reference	...
20 to 399 ft	118 (43, 237), n = 8	0.93 (0.62, 1.40)	.72
400 to 709 ft	587 (533, 619), n = 8	1.02 (0.71, 1.45)	.93
710 ft or greater	848 (743, 1032), n = 8	0.67 (0.43, 1.05)	.08

*Values are median (interquartile range) altitude and number of stadiums in that range.
†Values in parentheses are 95% confidence interval.
‡Multivariable analysis accounting for team and whether play was home or away.*

propriate for analysis. SAS PROC GENMOD (SAS Institute Inc, Cary, NC) was used for analysis of the data with binary outcomes and was used with a logit link function for both the dichotomized and 4-level categorical altitude-independent variables of interest.

A post hoc logistic regression analysis and evaluation of the maximal sensitivity and specificity of the receiver-operating-characteristic curve, utilizing the Youden index, was employed to evaluate the possibility of a data-driven cut point for concussion.

RESULTS

During the 2012 and 2013 regular seasons (weeks 1-16), there were 300 concussion events reported in the NFL, involving 284 players. The concussion incidence rate for the 2 seasons (counting only the 284 players) was 64.3 cases per 10 000 game exposures. When the data were evaluated relative to game field elevation, a statistically significant lower rate of concussion was noted at games played at higher-elevation stadiums (49.4 concussions per 10 000 game exposures) compared to games played at lower-elevation stadiums (70.0 concussions per 10 000 game exposures; *P* = .02). Thus, playing a game at higher elevation, as defined in this study, was associated with a 30% reduction in the odds of a concussion compared to playing a game at lower elevation (odds ratio = 0.70; 95% CI: 0.53, 0.94).

To further evaluate the effects of elevation on concussion incidence, a multivariable generalized linear model was used to examine the association between game field elevation and any concussion event by team per game, while controlling for season and week and also for clustering of team, at home and away. In this model, the dichotomization analysis, with 644 ft above sea level as the cut point, provided an odds ratio of 0.68 (95% CI: 0.47, 0.99; *P* = .04) for concussion in a game played at higher versus lower altitude (**TABLE 1**). Thus, similar to the simple model above, playing a game at higher elevation was associated with 32% lower odds of concussion compared to playing a game at lower elevation, as defined in this study.

Complementary analyses were performed to explore altitude and concussion incidence data for a potential "dose response" and to determine incidence rates using data-driven quartile cuts of the altitude levels of each stadium. The results of the quartile splits using 20 ft (6.1 m), 400 ft (121.9 m), and 710 ft (216.4 m) above sea level are presented in **TABLE 1**. Based on the results of the latter analysis, the potential threshold effect was further examined using the cut point of the upper quartile. Although not considered statistically significant, the results were very similar to those found using the 644-ft cut point, with the 710-ft cut point having an odds ratio of 0.68 (95% CI: 0.46, 1.01). It should be noted that week of play was a significant covariate in the models, although season (2012 versus 2013) was not. Post hoc area under the receiver-operating-characteristic curve from the logistic regression analysis showed a weak, not statistically significant, but confirmatory cut point at 635 ft (193.5 m), which is an equivalent dichotomization of stadium altitudes used in the current analysis (644 ft).

Descriptive statistics for mechanism of injury were also computed with this data set. No mechanism of injury was reported for 48.6% of the reported concussions. From those with a definitively stated mechanism of injury (n = 146), 67.1% of the reported concussions were the result of direct blows to the helmet. A direct blow to the helmet was defined as any body part from an opponent contacting the player's head (eg, knee to helmet, shoulder to face mask) versus specific helmet-to-helmet contact. Helmet-to-helmet impact resulted in 20.5% and helmet-to-field impact accounted for 12.3% of the total reported concussions. **TABLE 2** presents the mechanism-of-concussion breakdown for each year.

DISCUSSION

The current study investigated the relationship between NFL rates of concussion at game venues and the altitude of those venues. Specifically, playing an NFL game at higher elevation (644 ft [196.3 m] or greater) was associated with a 30% reduction in the odds of concussion (odds ratio = 0.70; 95% CI: 0.53, 0.94) compared to playing a game at lower elevation (less than 644 ft [196.3 m]). This reduction in concussion risk showed a similar trend, although not statistically significant, when adjusting elevation cut points based on quartile splits (high elevation of 710 ft [216.4 m] or greater). The current study pursued an epidemiological investigative meth-

TABLE 2 MECHANISM OF CONCUSSION BY SEASON*

Mechanism	2013	2012	Combined
Helmet to helmet†	16 (21.1)	14 (20.0)	30 (20.5)
Blow to helmet‡	48 (63.2)	50 (71.4)	98 (67.1)
Helmet to field§	12 (15.8)	6 (8.6)	18 (12.3)
Total	76 (100.0)	70 (100.0)	146 (100.0)‖

*Values are n (%).
†Helmet to helmet was classified as impact between the helmets of 2 players, typically occurring to the crown area.
‡Blow to helmet was defined as any other impact to the helmet area (eg, from a leg, torso, collision with another player) that was not a direct result of impact from another helmet.
§Helmet to field was classified as any impact directly between the player's helmet and the playing surface.
‖Of the reported concussions, 48.6% (n = 138) did not explicitly state the mechanism of injury. Secondary concussions to individual players were not included in the count (n=16).

odology similar to that of a previously performed study on high school football competition but focused on NFL data. Based on the current report, the NFL data are consistent with the lower rate of concussion previously reported at similar elevations in high school football.[29] Potential research into the mechanisms that underlie this reduction in concussion rates at increased altitude may provide a new pathway for research into primary prevention mechanisms for concussion in all populations.

The results of this evaluation of the association between altitude and reported concussion events in the NFL are consistent with a prior investigation of concussion incidence in high school athletes.[29] Simply stated, the findings of the current and prior study indicate that athletes playing football at or above 644 ft in altitude (up to 5192 ft) experienced fewer concussive events than those playing at lower elevations (below 644 ft). To further evaluate the significant difference in concussion events noted using the 644-ft (196.3-m) cut point in both our simple and multivariable models with the dichotomized altitude, a data-driven quartile split of altitude was analyzed, using the multivariable approach, to determine if there was a potential dose-response relationship of altitude. Instead, a possible threshold effect was observed, with a non–statistically significant (P = .08) cut point close to the upper quartile (710 ft [216.4 m]), which was also close to our a priori cut value obtained from the literature. In addition, when looking at the area under the receiver-operating-characteristic curve from the logistic regression analysis, we found a weak, not statistically significant, but confirmatory cut point of 635 ft (193.5 m). Based on these 2 confirmatory approaches, the use of a cut point of 644 ft from the prior epidemiological study in football was preferable and supported for use in the current investigation. The authors grant that further research with larger sample sizes and better control of confounding variables is needed to determine if there is an altitude at which the risk of concussion may be reduced. However, the current results were obtained from a robust analysis examining the effect of altitude, while also accounting for team and whether the game was home or away. In the same multivariate model, we also examined the effect of season and week of play. We were unable to control for factors such as mechanism of injury and true exposure hours. Likewise, temperature, design of the stadium (dome or open air), and oxygen use on the field may also need to be considered in future investigations. The noted relationship between higher altitude and reduced concussion incidence in the current study on NFL players, despite the potential confounders, provides evidence consistent with that described in a prior study in high school players.[29] The similar findings of these 2 studies suggest potential explanations or mechanisms for lower concussion rates at higher altitudes.

Although the hydrodynamics of the intracranial space were not measured, we can speculate that the physiological adaptations to higher altitude may be a potential explanation for reduced concussion incidence at increased altitude. Cerebral blood flow likely rises as a response to even mild hypoxemia (low oxygen levels), including hypoxic changes associated with increased elevations.[37] Restricted venous drainage as a result of this increased cerebral blood flow would result in cerebral venous engorgement and a subsequent rise in intracranial pressure when the limits of cerebral compliance are reached.[36] However, the relationship between increased altitude adaptation and mitigating concussive symptoms is unclear. It may be that some of the adaptive effects of the body to higher altitude may impart some protection against concussive symptoms. This hypobaric hypoxia may drive increases in cerebral blood flow that result in concomitant increases in intracranial pressure and volume.[36] The physiologies that occur during acclimatization to higher altitude, including the potential for reduced intracranial compliance (tighter fit), may benefit brain hydrodynamics during competitive sports.[19,29,36,38] While at extreme elevations the tighter fit of the brain can have serious negative health effects (eg, mountain sickness, high-altitude headache, and high-altitude cerebral edema), at lower altitudes we still expect alterations of physical and physiological parameters in the absence of negative sequelae, as minor changes in air density, humidity, temperature, and oxygen levels occur even up to the maximum elevation of 5192 ft used in this study. In the current investigation, reduced concussion rates were noted for elevations greater than 644 ft (196.3 m).

However, the authors acknowledge that this relationship may be due to reasons other than the proposed physiological response to elevation, and further verification is needed.

Specifically, it could be hypothesized that, with increased altitude, players who are not acclimatized may be more winded, tired, and lethargic, especially later in the game, and therefore unable to perform at their full potential when it comes to running, blocking, or tackling. This might result in a decrease in forces when collisions occur. However, these potential alternative explanations should also be considered in the context of the 644-ft threshold found in this study and the fact that only Sports Authority Field at Mile High in Denver, CO is purported to have a fatiguing effect on some NFL players. The other stadiums located above the cut scores in the present study are not typically viewed in the same way, thus it appears unlikely that increased fatigue is driving the reduction in concussion rates for altitudes above 644 ft.

A potentially greater confounder to the incidence rates was the inability to control for sideline oxygen use in the current analyses. Oxygen use would cause a substantial decline in cerebral blood flow and thus an increase in slosh. Perhaps this can help explain why Denver did not have the lowest rate of concussion. Similarly, caffeine use on the day of a game could alter brain compliance and influence concussion rates. Regardless, it is clear that more work is needed to fully understand the potential reasons or mechanisms underlying the results of this study.

For the concept of a tighter fit to make sense, one might consider a mere reduction in the total compensatory reserve of the cranium (estimated to be only 4 cc, or just 3% of total cerebral blood volume).[23] If the compliance of a rigid vessel is decreased by any mechanism (eg, increased intracranial volume), inertial cavitation (a speculated mechanism for concussion and severe traumatic brain injury) is less likely to occur, as sudden directional changes in fluids cannot develop to cause vapor cavities.[10,18,21,39,40] Although the absolute changes in physiologies at minimal altitude are quite small, the relative changes in oxygen partial pressure, oxygen saturation, and even the fraction of inspired oxygen are greatest at lower altitudes.[1] For example, when moving from 0 to 1000 ft, the alveolar oxygen partial pressure goes from 103.0 to 98.2, a decline of approximately 5%. This can be compared to going from 20 000 to 21 000 ft (still only a 1000-ft difference), which results in the alveolar oxygen partial pressure going from 34.3 to 33.5, a decline of approximately 2.3%.[20] Another example would be the actual oxygen concentration of 20.9% at sea level changing to just 20.1% at 1000 ft of altitude.[2] Considering this 4% change in oxygen provided, this seemingly small physical parameter could, in fact, be responsible for the above-postulated 4 cc of filled intracranial compliance and tighter fit.

While the current data set captures a very small window of time, there seems to be a slight increase or no change in helmet-to-helmet contacts from 2012 to 2013. This may suggest that simple rule changes may not be the most effective approach to reduce concussion in sport. The "law of unintended consequences" might also apply, given current speculation that rule changes for tackling strategies, for example, "aiming lower on a hit," could actually increase the relative incidence of other injury mechanisms. For example, defenders focused on low hits to tackle the oncoming opponent may increase the risk of an offensive player sustaining an anterior cruciate ligament injury that can result from a direct blow to the knee.[34] Likewise, it is possible in the same scenario that the defender may in fact increase their risk of concussion from a blow to the tackler's helmet by the offensive player's knee or thigh. While these proposed consequences of rule changes are speculative, focused efforts are needed to verify that rule changes are not actually increasing injury risk.

Limitations

There are several large discrepancies in reported concussions per season in the NFL among sources. For example, Concussion Watch[11] reported that 92 concussion injuries occurred in the 2009 season. However, in news articles by the Associated Press, 127 concussions were reported just in the first 8 weeks of the 2009 season.[3] Due to these discrepancies, the current investigation utilized a single reputable source that aggregates and confirms reports of incident concussions.[11] While there is not an expected altitude-based bias in the reporting of concussions, the authors acknowledge that a league-driven mechanism that supports the aggregation of injury tracking and exposures would benefit future analyses.

It is likely that several concussions over the last 2 years went unreported. In 2011, the Associated Press interviewed 44 current (at the time) NFL players regarding their attention to concussions during the season. Despite the warnings, 23 of the 44 players (53%) indicated that they would attempt to hide a concussion injury.[5] One year later, 56% of NFL players surveyed reported that they would also attempt to hide symptoms to avoid missing game time.[31] In addition, concussions that occurred prior to the team's bye week might not have been reported on the injury report. These scenarios present limitations regarding the reporting of concussions in the current study. The data set presented here only includes concussion injuries that were diagnosed and reported. The authors acknowledge that there are concussion injuries that go unreported and undiagnosed by players who are fearful of being sidelined and potentially losing their roster spot or missing an opportunity to demonstrate their worth to a team. Therefore, these data should be interpreted with caution.

A limitation of a previous study[29] that linked lower concussion incidence with higher-altitude locations in high school athletics was the varying levels of athletic competition throughout the nation.

This particular data set removes the potential for a varying level of competition because it consists only of professional football players in the NFL. Due to relatively low numbers of concussions, caution should be used when interpreting these results; using the a priori cut point of 644 ft has a 95% upper bound of 0.99, and the upper bound using 710 ft (upper quartile) crosses 1.0, with an upper limit of 1.05. However, the relationship between altitude level and concussion rates is strengthened by the current results. But it is not known if athletes accustomed to living at higher altitudes might have adapted to that environment, or if there are acute versus chronic effects of altitude on intracranial compliance. Likewise, another possible consideration is that games played at higher altitudes may result in a subtle change to the way in which football is played. These confounding variables should be evaluated in future prospective investigations. Further study is also needed to glean the potential effect of traveling to higher or lower altitudes for competition. Finally, the current data may be limited, as we did not have a direct measure of hydration status, prehydration, caffeine use, pharmaceuticals, anti-inflammatories, or pain-reliever medications prior to or during competition, all of which might have affected concussion incidence. More importantly, direct measurement of each athlete's supplemental oxygen usage on the sideline during competitions was not documented and was therefore unable to be controlled for in the current analyses. It is possible that some athletes, especially those unaccustomed to playing at higher altitudes, made use of supplemental oxygen on the sideline. This most likely negates the proposed benefits of hypoxia-induced edema gained at increased elevation. Because oxygen is known to decrease cerebral blood-flow velocity to the cranium,[28] further research may also be warranted to determine if there are effects of oxygen use on the sideline relative to the risk of concussion incidence during competitive football.

CONCLUSION

For regular-season games played in the first 16 weeks of the 2012 and 2013 regular NFL seasons, there was a statistically and clinically lower incidence of concussions for games played at altitudes above 644 ft. Relative to game field elevation, there was a 30% reduced odds of concussion when playing at higher elevation compared to playing at lower elevation. The results of this study in professional athletes are consistent with the results of a previous study on high school football players. Future investigation is warranted to confirm the relationship of increased altitude and the reduction in sports-related concussion in collision sports. If confirmed, efforts to determine underlying explanations for this relationship would be warranted and could potentially lead to intervention strategies aimed at reducing the number of concussions in contact sports. ◉

KEY POINTS

FINDINGS: Epidemiological data for the first 16 weeks of the 2012 and 2013 NFL football seasons indicated 300 concussions involving 284 players (64.3 primary cases per 10 000 game exposures). Relative to game field elevation, there was a 30% reduced odds of concussion (odds ratio = 0.70; 95% CI: 0.53, 0.94) when playing at higher elevation (greater than 644 ft [196.3 m] above sea level) compared to playing at lower elevation. Therefore, playing at a higher altitude may be associated with a reduction in sports-related concussion in NFL athletes.

IMPLICATIONS: The reported relationship between concussion incidence and elevation above sea level needs further verification. In addition, if validated, determining the underlying reasons for such a relationship may lead to strategies for reducing concussion injuries in contact sports.

CAUTION: While there is not an expected altitude-based bias in the reporting of concussions, the authors acknowledge that the current tracking and reporting of concussion events for NFL players are not optimal.

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