Older adults, particularly those housebound, are susceptible to vitamin D deficiency and insufficiency because of reduced sunlight exposure, inadequate nutrition, dermatological changes, and diminished renal function (Witham and Francis, 2014). Reduced levels of circulating serum 25-hydroxyvitamin D (25(OH)D) have been associated with muscle weakness and reduced bone mineral density (BMD), along with subsequent falls and fractures leading to increased nursing home admissions (Weaver et al., 2010). Chronic deficiency results in osteomalacia (bone softening; known as rickets in children), osteoporosis (porous bone), faster turnover of calcium metabolic activity, and an increase in production of parathyroid hormone (PTH), which exacerbates the process of weakening bones (Parfitt et al., 2011; Visser et al., 2003). Vitamin D is also suspected to be important for maintaining proper immune system operation and cognitive function (Buell et al., 2010; Holick, 2004). Vitamin D may also offer a protective factor in a broad range of diseases such as diabetes, cancer, multiple sclerosis, Alzheimer’s disease, and dementia (Buell et al., 2010; Holick, 2004; Lips, 2001; Parfitt et al., 2011). The most widely accepted treatment for insufficient and deficient vitamin D level is oral supplementation; however, some have noted that this

Correlation of objectively measured light exposure and serum vitamin D in men aged over 60 years

Alison J Fields, Steven E Linnville and Robert E Hoyt

Abstract
Diminished vitamin D is common among older individuals. Sunlight contributes more to vitamin D synthesis than diet or supplementation. This study examined associations between objectively measured light exposure, vitamin D serum levels, and bone biomarkers in 100 men aged over 60 years. Light exposure was measured in lux via Actigraph monitors for 1 week. Significantly, greater levels of vitamin D were observed in participants with higher light exposure. Seasonal differences in lux were also noted. Significant differences in bone markers were not found. Objective measurement of light exposure is an inexpensive, simple, and effective way to address vitamin D deficiency.

Keywords
deficiency, light, lux, objective measurement, vitamin D
method for addressing the end goals of increasing physical function and reducing falls may not provide these benefits (Cummings et al., 2016; Hansen et al., 2015; Moyer; U.S. and Preventive Services Task Force, 2013). While dietary intake and supplementation augment production of vitamin D and provide a sparing effect, light exposure has been documented to provide as much as 90 percent of an individual’s vitamin D requirement (Hall et al., 2010; Holick, 2004; Lips, 2001; Lips et al., 2014). However, the amount of light exposure necessary to positively affect 25(OH)D levels varies based on personal circumstances (Holick, 2004; Lips, 2001; Lips et al., 2014). Latitudinal location and time of year are two major determinants of vitamin D production. Those living in more northern locations may experience virtually no vitamin D production for nearly half of the year (Lips, 2001). Production is also heavily determined by skin composition as well. Vitamin D production is higher in lightly pigmented skin compared to heavily pigmented skin (Lips, 2001). Furthermore, the skin in senior adults can continue to produce the precursors of vitamin D, but research shows that this organ no longer does so as efficiently as during youth because of reduced 7-dehydrocholesterol levels (American Geriatrics Society Workgroup, 2013; MacLaughlin and Holick, 1985; Sakem et al., 2013). Also, in an effort to reduce skin cancer, public health organizations have given blanket recommendations to limit sun exposure and increase use of sunscreen, which could be reducing population levels of 25(OH)D (Sinha et al., 2013). It has been suggested that a minimal “10-min exposure of head and arms (unprotected) three times per week is adequate to prevent vitamin D deficiency” or “doses small enough to produce only minimal tanning” can create beneficial increases in 25(OH)D (Armas et al., 2007; Lips, 2001).

Current research has not consistently demonstrated beneficial effects or reduced risk of disease and falls in the older population with the exclusive use of oral vitamin D supplementation (Bolland et al., 2014; Hansen et al., 2015). However, despite continued debate on the role of supplementation in producing various positive outcomes, there is little doubt that sunshine is the most important contributor to healthy vitamin D levels (Autier et al., 2014; Theodoratou et al., 2014). Research in objective monitoring of light exposure in respect to vitamin D and bone markers may yield valuable insight into diagnostic and treatment protocols in the older population.

One of the routinely used means of collecting outdoor activity and light exposure is via sunlight exposure questionnaires. Advantages of these instruments include low cost, fairly uncomplicated administration, and standardization (Falk and Anderson, 2012). However, questionnaires may provide imprecise measurement of vitamin D status due to the wide variety of personal factors that inhibit vitamin D production, such as sunscreen use, clothing material, and melanin pigment (Cargill et al., 2013; McCarty, 2008). Wearable light detection monitors have the potential to become valuable objective tools whose benefits include cost effectiveness, small size, and light weight, practicality in participants’ natural environments, and allowance for monitoring over long-term periods (Martin and Hakim, 2011). This method is also an effective means of reducing recall and reporting bias that could negatively impact the data.

Previous research to determine a correlation between objectively measured light in lux (one lumen per square meter) and serum 25(OH)D levels has been limited and yielded mixed results. Calogiuri et al. (2013) found no significant differences in vitamin D levels for those in an outdoor versus indoor activity group but did find a small positive correlation between vitamin D levels and objectively measured light exposure. Their participant group was limited in size (14), and the timetable between light exposure and blood draws being less than 24 hours post-exposure may have been too short to have demonstrated a significant difference in vitamin D levels. In another similar study, researchers in Korea were unable to confirm a relationship between serum 25(OH)D and sunlight measured by objective means; however, they noted a small sample size (20 women) and low compliance with outdoor activity due to cold weather during their November collection period as potential limiting factors (Lee et al., 2012).

Clearly, institutionalized and/or housebound elderly individuals are at greater risk of vitamin D deficiency. So, what is the likelihood of vitamin D deficiency or insufficiency in an older population if they are relatively active? The Robert E. Mitchell Center for Prisoner of War Studies had a unique opportunity to measure light exposure in a prior research project where activity and sleep were measured, and lux was included. We sought to identify in the same cohort of 120 older men whether light levels, measured by lux as a feature of ActiGraph accelerometer monitors, correlated with vitamin D and associated bone metabolic biomarkers.

**Methods**

**Participants**

The participants were a subset of Vietnam-era repatriated prisoners of war (RPWs) from all branches of services, as well as a matched comparison group (CG) of combat veterans (who had been in similar combat but were never captured/imprisoned). They have been voluntary contributors to the Robert E. Mitchell Center for Prisoner of War studies annual medical and psychological follow-up program within the Department of Defense since 1973. Their ages range from 61 to 86 years (mean = 73, standard deviation (SD) = 5). This study comprises 100 participants (76 RPWs and 24 CGs) who took part in medical follow-up at the
Center between May 2012 and June 2013. Participants reported being in good physical health for their ages and were able to travel to the Mitchell Center in Pensacola, Florida, to engage in the study. Their average grip strength was above normal (45 kg) and their comfortable walking gait was on par with their age group (1.3 m/s) (Bohannon, 1997; Massey-Westropp et al., 2011). The majority of them were free from psychological diagnoses (76 participants). They supplied actigraphy and lux data and had a vitamin D assay collected as part of their routine medical follow-up. The other 20 from the original study (Fields et al., 2015) were omitted because they did not have a vitamin D assay collected at the time of actigraphy collection. Particulars of this cohort have been previously published (Segovia et al., 2013). This study was reviewed and approved by an institutional review board, and all participants included in this research have consented to being included in the study.

**Lux meters**

ActiGraph™ GT3X+ monitors (Actigraph™; LLC, Pensacola, FL, USA) with lux meters were used to gather exposure to light in our participants. These actigraphy monitors include triaxial accelerometers that identify movement, steps, kilocalories, as well as lux. The monitors have 512MB of memory and activity and light collection occurred at 30Hz. Participants wore the monitor for seven consecutive days and nights on their non-dominant wrist. Typical lux level estimates for the GT3X+ were as follows (Table 1).

**Procedures**

Blood samples were obtained as part of routine clinical practice, which included serum vitamin D, and other relevant bone biomarker data (calcium, phosphorous, and alkaline phosphatase). Actigraphy monitors with lux meters were scheduled to turn on when participants returned home.

### Table 1. Lux level estimates.

| Lux level estimate | Interpretation comparison                  |
|--------------------|-------------------------------------------|
| 1                  | Twilight                                  |
| 5                  | Minimal street lighting                   |
| 10                 | Sunset                                    |
| 50                 | Family living room                        |
| 80                 | Hallway                                   |
| 100                | Very dark overcast day                    |
| 320–500            | Office lighting                           |
| 400                | Sunrise/sunset                            |
| 1000               | Overcast day                              |
| 10,000–25,000      | Full daylight                              |
| 32,000–130,000     | Direct sunlight                           |

Source: Hawks (2012).

### Table 2. Descriptive analysis of seasonal quartiles and mean lux differences.

| Season quartiles | N     | Mean lux | Standard deviation |
|------------------|-------|----------|--------------------|
| Fall             | 34    | 151.7    | 181.8              |
| Winter           | 26    | 84.5     | 77.0               |
| Spring           | 18    | 228.4    | 224.8              |
| Summer           | 22    | 296.3    | 158.8              |
| Total            | 100   | 179.9    | 180.7              |

Lux levels were collected for 7 days and nights from 92 of the 100 participants. Of the remaining eight participants, seven wore the ActiGraph for 6 days, and therefore, lux was gathered for only those 6 days, and one participant wore the ActiGraph for only 4 days. These eight had forgotten to put on the device at the designated time.

**Data analysis**

A vitamin D assay of 30–100 ng/mL is widely considered within normal limits. Using this criterion as a cut point for normal (≥30 ng/mL) and abnormal (<30 ng/mL) vitamin D levels, the data were divided into these two groupings to compare average daily light (in lux) exposure collected from the ActiGraph and the associated bone metabolic biomarkers. Since it took a year to collect this amount of data, seasonal differences had to be accounted for as well. The data were divided into the four seasons based on the official calendar start of the season in the northern hemisphere (i.e. fall, 21 September; winter, 21 December; spring, 21 March; summer, 21 June).

### Results

Descriptive statistics of seasonal quartiles and mean lux illustrated differences in mean lux levels, particularly for fall and winter (see Table 2). A Bonferroni post-hoc alpha adjusted to $p = .0125$ (for four comparisons) indicated that winter lux levels were significantly lower than summer levels ($p = .0001$; large effect size = 1.75), and fall levels were significantly lower than summer levels ($p = .011$; large effect size = .803); but, spring versus winter was not significant because of the adjusted alpha for multiple comparisons. There were no significant differences between remaining seasonal levels (see Table 3).

Descriptive statistics of vitamin D cut points between normal and abnormal serum levels showed mean lux differences (see Table 4). Independent $t$ tests demonstrated statistically significant differences in mean lux levels between the two groups, $t(98)=2.53$, $p = .013$. This difference was moderate in effect size ($Cohen’s d = .51$). The analysis of variance (ANOVA) for vitamin D by normal/abnormal levels was found to be significant ($F(1, 98)=6.38$, $p = .013$, small effect size = .03) (Table 5).
Descriptive statistics of seasonal mean lux and vitamin D cut points between normal and abnormal serum levels illustrated some mean lux differences (see Graph 1). However, with the exception of the fall season, independent t-tests demonstrated no significant differences in mean lux levels between the two vitamin D groupings. Fall season’s significant mean lux difference between the two groups demonstrated a large effect size (Cohen’s d = 1.27).
The ANOVA for vitamin D by the four seasonal levels was found to be significant ($F(3, 96)=7.36$, $p=.0001$) (Table 6).

Descriptive statistics of the associated bone metabolic biomarkers showed no differences in the mean levels between the normal and abnormal vitamin D groupings, with the exception of possibly alkaline phosphatase. However, independent $t$-tests showed no statistically significant differences in any of these bone metabolic markers (calcium, $t(98)=1.50$, $p=.137$; phosphorous, $t(98)=.913$, $p=.364$; alkaline phosphatase, $t(79.6)=1.50$, $p=.138$).

Discussion

For this cohort, sunlight exposure translated into significantly higher levels of vitamin D, which is congruent with previous research. This finding was expected since there is a direct correlation between exposure to ultraviolet B (UVB) and serum concentrations of vitamin D. While the associations were not robust across all potential interactions between objectively collected light and vitamin D values, some of the associations were significant and indicate that further evaluation within a larger and more controlled design is prudent. A broad range of personal factors could have influenced the data including diet, clothing choice, and sunscreen use.

While there is no globally accepted stratum defining vitamin D values, a vitamin D assay of 30–100 ng/mL is commonly considered within normal limits. Using this criterion as a cut point for normal and abnormal vitamin D levels and comparing with average daily light (in lux) exposure collected from ActiGraph monitors, this study was able to partially establish anticipated seasonal differences in lux levels with winter and fall lux rates significantly lower than summer. These differences may be based upon seasonal sunlight variations as well as more amenable weather conditions that contribute to extended outdoor exposure. Also observed was an overall interaction between objectively measured sunlight with serum vitamin D levels showing that participants with abnormal vitamin D levels had significantly less average daily light exposure compared to those within normal limits of vitamin D. A significant increase in both lux values and vitamin D were observed during the fall season only. Contrary to expectation, the light exposure and vitamin D interaction was not significant across all seasons nor was it associated with bone metabolic markers.

Limitations

The use of a cohort of aged Caucasian men from a high socioeconomic status restricts the ability to generalize results to the average US population. Also, there were no data collected on diet, nutritional supplementation, or sunscreen use for the participants. Additionally, serum PTH levels may have provided additional insight but were not part of the routine laboratory tests. Finally, this study is a cross-sectional study, and causality cannot be determined. Despite these constraints, it is important to note that our findings are similar to results observed in previous research demonstrating the importance of continued research into objectively measured sunlight on the production of vitamin D and overall bone health.

Conclusion

With a large portion of the US population diagnosed with abnormal vitamin D levels and associated costs of fall-related injuries estimated in the billions of dollars, it is important to explore all available avenues of diagnosis and treatment of abnormal vitamin D. Today’s advances in technology have contributed to the production of smaller and less invasive personal health monitoring devices; the use of light meters to objectively obtain personal data on light exposure could offer healthcare providers, patients, and caregivers an opportunity to reliably evaluate reduced sunlight as a potential impediment to positive overall health. They could also provide a uniquely accurate and reliable tool for treatment and evaluation of any benefits received by sunlight therapy. Future research of vitamin D levels in older populations would benefit from the continued use of objectively measured sunlight exposure while controlling for such factors as dietary and supplementation intake of vitamin D as well as sunscreen use.

Acknowledgements

This article is a product of the Robert E. Mitchell Center for Prisoner of War Studies and was supported by a grant (ONR-FY13 N0001413AF00002) from the Office of Naval Research (ONR). The findings and conclusions in this article are those of the authors and do not necessarily represent the official position of the ONR or the Department of the Navy. The Robert E. Mitchell Center for Prisoner of War Studies would like to take this opportunity to give thanks to all our patrons for their participation in our studies, who make our research possible. To all our RPWs, we thank you for your courage, honor, and commitment. The staff of the Robert E.
Mitchell Center is also to be commended for the high standard of healthcare provided to our patrons.

Declaration of conflict of interests
The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding
The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by a grant (ONR-FY13 N0001413AF00002) from the Office of Naval Research (ONR). The findings and conclusions in this article are those of the authors and do not necessarily represent the official position of the ONR or the Department of the Navy.

References
American Geriatrics Society Workgroup (2013) Recommendations abstracted from the American Geriatrics Society consensus statement on vitamin D for prevention of falls and their consequences. Journal of the American Geriatrics Society 62(1): 147–152.

Armas LA, Dowell S, Akhter M, et al. (2007) Ultraviolet-B radiation increases serum 25-hydroxyvitamin D levels: The effect of UVB dose and skin color. Journal of the American Academy of Dermatology 57(4): 588–593.

Autier P, Boniol M, Pizot C, et al. (2014) Vitamin D status and ill health: A systematic review. The Lancet, Diabetes & Endocrinology 2(1): 76–89.

Bhonnor RW (1997) Comfortable and maximum walking speed of adults aged 20–79 years: Reference values and determinants. Age and Ageing 26: 15–19.

Bolland MJ, Grey A, Gamble GD, et al. (2014) The effect of vitamin D supplementation on skeletal, vascular, or cancer outcomes: A trial sequential meta-analysis. The Lancet, Diabetes & Endocrinology 2(4): 307–320.

Buell JS, Dawson-Hughes B, Scott TM, et al. (2010) 25-Hydroxyvitamin D, dementia, and cerebrovascular pathology in elders receiving home services. Neurology 74(1): 18–26.

Buell JS, Scott TM, Dawson-Hughes B, et al. (2009) Vitamin D is associated with cognitive function in elders receiving home health services. Journals of Gerontology Series A: Biological Sciences and Medical Sciences 64(8): 888–895.

Calogiru G, Mikkila S and Weydahl A (2013) Can promotion of outdoor activities impact people’s vitamin D levels? In: Proceedings of the 2nd electronic international interdisciplinary conference, Zilina, September, pp. 276–280. Zilina: EDIS–Publishing Institution of the University of Zilina.

Cargill J, Lucas RM and Gies P (2013) Validation of brief questionnaire measures of sun exposure and skin pigmentation against detailed and objective measures including vitamin D status. Photochemistry and Photobiology 89(1): 219–226.

Center for Disease Control (CDC) (2014) Costs of falls among older adults. Available at: http://www.cdc.gov/homeandrecreationalsafety/falls/fallcost.html (accessed 17 August 2015).

Cummings SR, Kiel DP and Black DM (2016) Vitamin D supplementation and increased risk of falling: A cautionary tale of vitamin supplements retold. JAMA Internal Medicine 176(2): 171–172. DOI: 10.1001/jamainternmed.2015.7568.

Falk M and Anderson CD (2012) Measuring sun exposure habits and sun protection behaviour using a comprehensive scoring instrument—An illustration of a possible model based on Likert scale scorings and on estimation of readiness to increase sun protection. Cancer Epidemiology 36(4): e265–269.

Fields AJ, Hoyt RE, Linnville SE, et al. (2015) Physical activity, sleep, and C-reactive protein as markers of positive health in resilient older men. Journal of Health Psychology. Epub ahead of print 10 February. DOI: 10.1177/1359105314568578.

Hall LM, Kimlin MG, Aronoy PA, et al. (2010) Vitamin D intake needed to maintain target serum 25-hydroxyvitamin D concentrations in participants with low sun exposure and dark skin pigmentation is substantially higher than current recommendations. Journal of Nutrition 140(3): 542–550.

Hansen KE, Johnson RE, Chambers KR, et al. (2015) Treatment of vitamin D insufficiency in postmenopausal women: A randomized clinical trial. JAMA Internal Medicine 175(10): 1612–1621. DOI: 10.1001/jamainternmed.2015.3874.

Hawks L (2012) Lux measurements. Available at: https://help.theactigraph.com/entries/22389373-Lux-Measurements (accessed 17 August 2015).

Holick MF (1996) Vitamin D and bone health. Journal of Nutrition 126(Suppl. 4): S1159–S1164.

Holick MF (2004) Sunlight and vitamin D for bone health and prevention of autoimmune diseases, cancers, and cardiovascular disease. American Journal of Clinical Nutrition 80(suppl. 6): S1678–S1688.

Laurentani F, Maggio M, Valenti G, et al. (2010) Vitamin D in older population: New roles for this ‘classic actor’? Aging Male 13(4): 215–232.

Lee S, Park S, Kim K, et al. (2012) Effect of sunlight exposure on serum 25-hydroxyvitamin D concentration in women with vitamin D deficiency: Using ambulatory lux meter and sunlight exposure questionnaire. Korean Journal of Family Medicine 33(6): 381–389.

Lips P (2001) Vitamin D deficiency and secondary hyperparathyroidism in the elderly: Consequences for bone loss and fractures and therapeutic implications. Endocrine Reviews 22(4): 477–501.

Lips P, Van Schoor NM and De Jongh RT (2014) Diet, sun, and lifestyle as determinants of vitamin D status. Annals of the New York Academy of Sciences 1317: 92–98.

Looker AC, Johnson CL, Lacher DA, et al. (2011) Vitamin D status: United States, 2001–2006. NCHS Data Brief 59: 1–8.

McCarty CA (2008) Sunlight exposure assessment: Can we accurately assess vitamin D exposure from sunlight questionnaires? American Journal of Clinical Nutrition 87(4): 1097S–1101S.

MacLaughlin J and Holick MF (1985) Aging decreases the capacity of human skin to produce vitamin D3. Journal of Clinical Investigation 76(4): 1536–1538.

Martin JL and Hakim AD (2011) Wrist actigraphy. Chest 139(6): 1514–1527.
Massey-Westropp NM, Gill TK, Taylor AW, et al. (2011) Hand grip strength: Age and gender stratified normative data in a population-based study. *BMC Research Notes* 4: 127–131.

Moyer VA; U.S. and Preventive Services Task Force (2013) Vitamin D and calcium supplementation to prevent fractures in adults: U.S. Preventive Services Task Force recommendation statement. *Annals of Internal Medicine* 3(158): 691–696.

Parfitt AM, Gallagher JC, Heaney RP, et al. (2011) Vitamin D and bone health in the elderly. *American Journal of Clinical Nutrition* 93(3): 549–555.

Sakem B, Nock C, Stanga Z, et al. (2013) Serum concentrations of 25-hydroxyvitamin D and immunoglobulins in an older Swiss cohort: Results of the Senior Labor Study. *BMC Medicine* 11: 176.

Segovia F, Moore JL, Linnville S, et al. (2013) Sleep and resilience: A longitudinal 37-year follow-up study of Vietnam repatriated prisoners of war. *Military Medicine* 178(2): 196–201.

Sinha A, Cheetham TD and Pearce SH (2013) Prevention and treatment of vitamin D deficiency. *Calcified Tissue International* 92: 207–215.

Theodoratou E, Tzoulaki I, Zgaga L, et al. (2014) Vitamin D and multiple health outcomes: Umbrella review of systematic reviews and meta-analyses of observational studies and randomised trials. *British Medical Journal* 348: g2035.

Visser M, Deeg DJ and Lips P (2003) Low vitamin D and high parathyroid hormone levels as determinants of loss of muscle strength and muscle mass (Sarcopenia): The longitudinal aging study Amsterdam. *Journal of Clinical Endocrinology and Metabolism* 88(12): 5766–5772.

Weaver SP, Passmore C, Collins B, et al. (2010) Vitamin D, sunlight exposure, and bone density in elderly African American females of low socioeconomic status. *Family Medicine* 42(1): 47–51.

Witham MD and Francis G (2014) Vitamin D in older people. *Reviews in Clinical Gerontology* 24: 158–171.