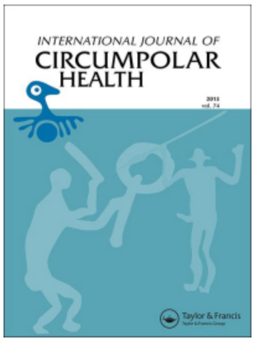

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Raynaud's phenomenon in the feet of Arctic open-pit miners

Albin Stjernbrandt [a], Hans Pettersson [a], Per Vihlborg [b], Anje Christina Höper [c,d], Anna Aminoff [c,d], Jens Wahlström [a] and Tohr Nilsson [a]

[a]Section of Sustainable Health, Department of Public Health and Clinical Medicine, Umeå University, Umeå, Sweden; [b]Department of Geriatrics, Faculty of Medicine and Health, Örebro University, Örebro, Sweden; [c]Department of Occupational and Environmental Medicine, University Hospital of North Norway, Tromsø, Norway; [d]Department of Community Medicine, UiT The Arctic University of Norway, Tromsø, Norway

ABSTRACT

The literature on Raynaud's phenomenon (RP) in the feet is scarce, especially in the occupational setting. The primary aim of our study was to investigate the occurrence of RP in the feet of miners. As part of the MineHealth project, written surveys and clinical examinations were completed by 260 Arctic open-pit miners working in northern Sweden and Norway (participation rate 53.6%). Data on RP were collected using standardised colour charts and questionnaire items. Clinical examination included assessing the perception of vibration and pain in both feet. There were eight women and three men who reported RP in the feet. Four also had RP in their hands but none acknowledged any first-degree relatives with the condition. Nine reported exposure to foot-transmitted vibration and one to hand-arm vibration. Seven showed signs of neurosensory injury in the feet. To conclude, the occurrence of RP in the feet of miners was 4.4%. Most cases with RP in the feet did not report the condition in the hands and were exposed to vibration transmitted directly to the feet. There were no reports of a hereditary component. Most cases with RP in the feet also had clinical findings suggestive of peripheral neuropathy in the feet.

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Introduction

Raynaud's phenomenon (RP) is a condition characterised by paroxysmal vasospasm in the small blood vessels of peripheral tissues [1]. It is most often seen in the fingers but has also been reported in other parts of the body such as the toes, nose, earlobes, nipples, and tongue [2]. Raynaud's phenomenon can be considered primary (i.e. idiopathic) or secondary to a range of conditions such as rheumatic diseases and exposure to hand-arm vibration (HAV) [3]. Onset in adolescence and symmetrical distribution of RP in both hands are often considered indications of primary origin, as is the concomitant engagement of the feet [4]. However, there have also been several reports about vibration-induced RP affecting only the toes [5].

HAV exposure indicates that oscillatory motions are transmitted to the human body through the upper extremity [6,7]. Most often, this occurs when a worker is gripping a vibrating handheld tool. When vibration is transferred through surfaces supporting the body, such as floors, seats, or backrests, the exposure is commonly termed whole-body vibration (WBV) [6,8]. However, some authors have suggested that exposure that occurs solely through standing or resting the feet on vibrating floors or machinery should instead be called foot-transmitted vibration (FTV) [5], which we find more accurate.

To our knowledge, only a few case reports and small series have described vibration-induced RP in the feet [9–17], and these are summarised in Table 1. In brief, all published cases had exposure to FTV with a duration ranging from 2 to 50 years. In most cases, HAV exposure and vibration-induced RP in the hands were also reported. However, there have been no previous studies on open-pit mines in the Arctic setting, where exposure to both vibration and cooling conditions can be intense. In the previous literature, two major explanations for RP in the feet among vibration-exposed workers have been proposed. The most intuitive is a direct effect of vibration transmitted to the feet, causing mechanical injury to peripheral vessels and nerves [5,17]. In such instances, the worker does not necessarily have to be exposed to HAV or present with any symptoms in the upper extremities. The second proposed mechanism is that vibration transmitted through the hands may have a systemic effect and increase the vascular tone in the entire body [17,18]. Apart from vascular effects, neurosensory

CONTACT Albin Stjernbrandt albin.stjernbrandt@umu.se Section of Sustainable Health, Department of Public Health and Clinical Medicine, Umeå University, Umeå 901 87, Sweden

Table 1. Previously published reports of vibration-induced Raynaud's phenomenon in the feet.

Author and year	Occupation (number of cases)	RP hands	HAV	FTV	Exposure source	Exposure duration (years)
Mills 1942 [9]	Road worker (1)	N	Y	Y	Pneumatic hammer	-
Suzuki et al. 1966 [10]	Quarry worker (1)	N	Y	Y	Rock drill	-
Gomibuchi et al. 1967 [11]	Forestry worker (1)	Y	Y	Y	Chainsaw Forest machine	-
Hashiguchi et al. 1988 [12]	Forestry worker (1) Miners (2)	Y	Y	Y	Chainsaw Rock drill Stone crusher	-
Hedlund 1989 [13]	Miners (6)	Y	Y	Y	Rock drill on platform	2–26
Tingsgård et al. 1994 [14]	Farmer (1)	N	N	Y	Wagon	12
Toibana et al 1994 [15]	Forestry workers (4) Rock-drillers (5) Quarry worker (1) Welder (1)	Y	Y	Y	Chainsaw Rock drill Stone crusher Concrete breaker Chipping hammer	18–50
Choy et al. 2008 [16]	Quarry worker (1)	Y	Y	Y	Rock drill	30
Thompson et al. 2010 [17]	Miner (1)	N	Y	Y	Tunnel bolting machine	18
Eger et al. 2014 [5]	Raise workers (2)	Y	Y	Y	Jackleg drill	9–35
	Drill operator (1)	-	Y	Y	Jumbo drill	

RP: Raynaud's phenomenon, HAV: hand-arm vibration, FTV: foot-transmitted vibration.

injury to the hands of HAV-exposed workers is also well established, and it is plausible that an analogous condition could be found in the feet, although this has not been thoroughly studied. However, in two of the previously mentioned studies, concomitant signs of nerve injury in the lower extremities were reported [14,16]. In addition, neurophysiological studies on HAV-exposed workers have also shown reduced conduction velocities in peripheral nerves in the lower extremities [19–21].

In a review article on the relationship between hand-arm vibration and clinical manifestations in the lower extremities, the author concludes that there is some epidemiological and experimental evidence to suggest that HAV-induced vascular effects in the hands are associated with similar effects in the feet, such as subjective coldness, reduced skin temperature, and RP [22]. However, there is yet insufficient evidence to argue that such conditions in the lower extremities are associated with HAV exposure in the absence of upper extremity symptoms, or that FTV exposure could be an independent aetiological factor. Moreover, the author concludes on insufficient evidence for any association between vibration exposure and neurological symptoms or findings in the feet [22]. Therefore, further epidemiological studies assessing vascular and neurosensory conditions in the feet of vibration-exposed workers, independently of hand symptoms, are encouraged.

The data used in our study came from a project in open-pit mines in the Arctic region. As the existing literature is scarce and dominated by case reports or series, the primary aim of our study was to investigate the occurrence of RP in the feet of a larger group of workers exposed to HAV and FTV. Secondary aims included suggesting potential aetiologies for RP in the feet as well as assessing clinical signs of neurosensory injury in the feet.

Materials and methods

Study design and setting

Our study was based on the MineHealth project that has previously been extensively described [23]. Data were collected between November 2012 and November 2013 in two open-pit mines in northern Sweden and Norway, that were both located above the Arctic Circle. The study invited all men and women working in the mines, regardless of occupation. All subjects were provided oral and written information about the study before giving written consent to participate, and the study protocol was approved by the Regional Ethical Review Board for medical research in Umeå, Sweden (DNR 2012–365-31 M) and in Oslo, Norway (DNR 2013/1026/REK).

Description of materials

The study protocol was developed by the MineHealth consortium and consisted of two extensive questionnaires that were largely based on the Nordic Musculoskeletal Questionnaire [24] and the VIBRISKS survey [25]. The questionnaires included items on gender, age, length, weight, tobacco habits, education, occupational title, physical workplace exposures, previous injuries and diseases, as well as vascular and neurosensory symptoms in the hands and feet. There was a separate section devoted to RP that included a previously developed colour chart to identify RP [26,27]. For the hands, the subjects were asked about age of onset, triggering factors, frequency of attack as well as family history among parents, siblings, and children. Finally, the study participants were asked if they also suffered from RP in the toes. Other medical conditions were asked about using the following subheadings: cardiovascular, respiratory, neurological, psychiatric, musculoskeletal, rheumatic, dermal, renal, genital, gastro-enteral, malignant, endocrine, and ocular. Current prescription medication was collected in free-form text. Subjects were asked to specify how many hours per day they typically worked with hand-held vibrating machines, as well as outdoors or in unheated buildings or machines. They were also asked about how many hours per day they operated different categories of vehicles. These categories were customised to fit the vehicle types used at each worksite: 12 categories in the Swedish and 11 in the Norwegian mine. Examples of vehicles used in the mines include haul trucks (CAT 793 and 795, Volvo A25 and A40, Komatsu HD605), wheel loaders (CAT 962 and 980, Volvo L220, Ljungby Maskin L18, TORO 501), bulldozers (CAT D10), and drill rigs (Epiroc Pit Viper 351, Tamrock Ranger 700).

All questionnaire responders were also asked to participate in a health examination performed by consultant physicians specialised in occupational and environmental medicine. During this examination, sensory function in the big toe of both feet was examined using several clinical tests: vibration perception was evaluated using a tuning fork of 128 Hz and the VibraTip tool (McCallan Medical Ltd, Nottingham, Great Britain); sharp pain using an upholstery needle; and allodynia using a standardised pressure algometer (Somedic SenseLab AB, Sösdala, Sweden).

FTV exposure levels were estimated through WBV measurements that were conducted on a sample of mining vehicles according to ISO 2631–1 [8], using a HVM-100 instrument (Larson Davis, Depew, USA) and a standardised rubber seat pad with accelerometers for the three orthogonal axes, and these assessments have previously been described in detail [28]. No measurements were performed on ore crushers, and we therefore used previous Canadian data for exposure assessment in this instance [5].

Statistical analysis

Numerical data were described as median values with interquartile range (IQR), while categorical variables were presented as numbers and valid row percentages unless otherwise specified. Missing data were omitted from analyses. Pearson's chi-squared test was used to evaluate the distribution of categorical variables. Statistical analyses were performed using IBM SPSS Statistics for Windows (Version 28, IBM Corporation, Armonk, NY, USA).

Results

Participants and descriptive data

There were 260 subjects who were willing to participate in the study out of the total of 485 workers listed on the employee rosters (participation rate of 53.6%). There were 177 (70.2%) men and 75 women, with a median (IQR) age of 44 (20) and 35 (18) years, respectively.

Occurrence of Raynaud's phenomenon in the hands and feet

There were 29 men (17.2%) and seven women (9.9%) that reported RP in the hands. Among these, two men and two women also reported RP in the feet. In addition, there was one man and six women who reported only having RP in the feet but not in the hands. Therefore, in total, there were three men (1.7%) and eight women (10.8%) with RP in the feet, bringing the overall occurrence to 4.4%. The age of cases with RP in the feet ranged from 25 to 51 years. Details on each case are presented in Table 2.

Possible etiologies for Raynaud's phenomenon in the feet

In comparison with the rest of the study participants, the cases with RP in the feet were more often women and reported habitually cold feet as well as generalised abnormal cold sensitivity (Table 3). Cases with RP in the feet also reported more thermal discomfort in the toes in mild winter conditions (ambient temperature + 5 to − 5°C). None of the cases with RP in the feet had any first-degree relative (parent, sibling, or child) with RP in any location. One case had Sjögren's syndrome and received systemic anti-inflammatory treatment, another had ankylosing spondylitis but received no prescription treatment. Two cases had hypertension and one was treated with a beta-adrenergic receptor antagonist. Six cases worked outdoors or in unheated buildings or machines, and the daily exposure time ranged from 1 to 6 hours. In addition, four cases had previously contracted local cold injuries, but the type and location was not specified. Two cases were current cigarette smokers and one of these also used oral moist tobacco (snuff).

Out of the 11 cases with RP in the feet, only one reported exposure to HAV. This subject worked as

Table 2. Detailed information on the cases that reported Raynaud's phenomenon in the feet.

Case	Sex (male/female)	Age (years)	BMI (kg/m^2)	Smoking (yes/no)	Occupation	RP hands (yes/no)	Heredity RP (yes/no)	Diseases	Medication	Outdoor work (yes/no)	Local cold injury (yes/no)	HAV (yes/no)	FTV (yes/no)
I	M	51	27.7	N	Driller and loader	Y	N	Diabetes Hypertension	Insulin Enalapril Amlodipine	Y	Y	N	Y
II	F	49	22.4	N	Vehicle operator	Y	N			N	N	N	Y
III	M	45	25.9	Y	Mechanic and welder	Y	N	Psoriasis		Y	Y	Y	Y
IV	F	35	31.0	N	Production service technician	N	N	Hypertension	Metoprolol Bendroflumethiazide Desogestrel	Y	Y	N	Y
V	F	35	24.5	N	Support staff	N	N			Y	-	N	Y
VI	F	33	25.2	N	Support staff	N	N	Ankylosing spondylitis		N	N	N	N
VII	M	27	21.6	N	Crusher operator	N	N			N	N	N	Y
VIII	F	27	21.7	N	Ore sampler	N	N			Y	N	N	Y
IX	F	25	23.1	N	Vehicle operator	N	N			Y	-	N	Y
X	F	53	30.5	N	Vehicle operator	Y	N			N	Y	N	Y
XI	F	28	25.1	Y	Chef	N	N	Sjögren's syndrome	Prednisolone Hydroxychloroquine	N	N	N	N

BMI: body mass index, RP: Raynaud's phenomenon, HAV: hand-arm vibration, FTV: foot-transmitted vibration.

a mechanic and welder and reported using vibration handheld tools for less than half an hour per day. Using acceleration values for an angle grinder (4.5 m/s^2) as well as an impact wrench (7.0 m/s^2) and the reported exposure time, the cumulative HAV exposure was calculated to be about 0.9 to 1.4 m/s^2 A(8). In contrast, nine cases reported exposure to FTV, with exposure duration between 2 to 9 hours per day. One of these nine cases was employed on a drilling rig and another on a vibrating ore crusher, and in both instances, the floors were vibrating. The other seven cases were drivers of different kinds of mining vehicles, where the feet were in contact with pedals and floors that vibrated when driving over course terrain. According to measured vibration values in combination with reported exposure times, the cumulative FTV exposure ranged from about 0.2 to 0.8 m/s^2 A(8). As the FTV exposure levels were calculated based on WBV exposure, it can be concluded that four cases exceeded the exposure action value of 0.5 m/s^2 A(8) while none exceeded the exposure limit value of 1.1 m/s^2 A(8) for WBV (Table 4).

Neurosensory function in the feet

Of the 11 cases with RP in the feet, seven (64%) were found to have allodynia, six (55%) reduced perception of vibration, and four (36%) reduced pain perception. Details regarding the clinical examinations are presented in Table 5.

Discussion

Interpretation of findings

The occurrence of RP in the feet was 4.4% in this cohort of Arctic open-pit miners. There are no previous prevalence studies to compare with. However, in one previous study from Japan, 11 cases were encountered among about 1,000 vibration-exposed workers, suggesting an occurrence of around 1%. The prevalence of RP in the hands is consistently higher in Scandinavian countries compared to the rest of the world [29] and this is most likely due to the colder climate that triggers vasospastic attacks [30]. In analogy, it appears plausible that the occurrence of RP in the feet should also be higher in Sweden and Norway compared to countries with warmer climate, but further studies are needed to confirm this notion. The cases with RP in the feet in our study also reported abnormal cold sensitivity and habitually cold feet. These findings are in line with previous literature, that has reported on coldness and reduced tolerance to cold provocation in

Table 3. Comparison between subjects with and without Raynaud's phenomenon in the feet.

		Raynaud's phenomenon in the feet				
		Yes		No		
Variable	Categories	N	%	N	%	p value
Participants	–	11	4.4	239	95.6	-
Age (years)	18–29	4	36.4	57	24.1	0.449
	30–41	3	27.3	60	25.3	
	42–53	4	36.4	78	32.9	
	54–64	0	0.0	42	17.7	
Sex	Male	3	27.3	171	72.2	0.001
	Female	8	72.7	66	27.8	
Body mass index (kg/m^2)	BMI <18.5	0	0.0	1	0.4	0.938
	18.5≤BMI <25	5	45.5	87	36.4	
	25≤BMI <30	4	36.4	98	41.0	
	BMI >30	2	18.2	53	22.2	
Smoking	Yes	2	18.2	52	22.4	0.741
	No	9	81.8	180	77.6	
Educational level (years of schooling)	Elementary (≤9)	2	18.2	26	11.1	0.765
	High school (10–12)	6	54.5	143	61.1	
	Advanced (>12)	3	27.3	65	27.8	
Hand-arm vibration exposure (hours/day)	None	10	90.9	160	69.9	0.297
	One or less	1	9.1	44	19.2	
	More than one	0	0.0	25	10.9	
Whole-body vibration exposure (hours/day)	None	4	36.4	56	23.4	0.556
	Four or less	3	27.3	96	40.2	
	More than four	4	36.4	87	36.4	
Thermal comfort in the toes in mild winter conditions (ambient temperature + 5 to – 5°C)	Warm or neutral	0	0.0	16	11.4	0.003
	Neutral	2	28.6	102	72.9	
	Cold	4	57.1	18	12.9	
	Very cold	1	14.3	4	2.9	
Thermal comfort in the toes in harsh winter conditions (ambient temperature – 10 to – 20°C)	Warm or neutral	0	0.0	7	5.6	0.610
	Neutral	2	28.6	57	45.2	
	Cold	3	42.9	44	34.9	
	Very cold	2	28.6	18	14.3	
Ankle or foot pain during the last 12 months	Yes	3	27.3	35	14.6	0.413
	No	8	72.7	191	79.9	
Limited in daily work because of ankle or foot pain during the past month	Not at all	10	90.9	218	91.2	0.906
	Slightly	1	9.1	8	3.3	
	Moderately	0	0.0	2	0.8	
	Very	0	0.0	1	0.4	
	Unable to work	0	0.0	1	0.4	
Habitually cold feet	Yes	10	90.9	77	32.4	<0.001
	No	1	9.1	161	67.6	
Abnormal sweating of hands or feet	Yes	4	36.4	36	15.1	0.060
	No	7	63.6	203	84.9	
Abnormal cold sensitivity	Yes	5	71.4	45	19.9	0.001
	No	2	28.6	181	80.1	

Valid column percentages are presented.

the lower extremities of subjects with HAV exposure and vibration-white fingers [15,31,32].

In our study, RP in the feet was more prevalent among women than men, and this could be interpreted as a sex-related susceptibility due to hormonal factors [33], in analogy with RP in the hands which is also more common among women [29]. However, it is important to note that female workers were dominant among vehicle operators (and mostly driving haul trucks) in the Swedish mine, and this could mean that women were more exposed to FTV compared to men. Our experience during the data collection was that the drivers usually took off their shoes when driving the haul trucks and this could have increased exposure to vibration compared to if they had been wearing shoes [34]. One interesting finding was that only one case was exposed to HAV and only four reported also experiencing RP in the hands. Most previous reports have studied only HAV-exposed workers or considered RP in the feet to be an associated condition among those with vibration-induced white fingers in the hands [22]. Our findings challenge this concept and suggest that RP in the feet can develop independently and without HAV exposure, which is in line with two case reports [14,17]. Rather, the exposure to FTV might be of larger importance for the development of RP in the feet, although none of the cases in our study exceeded the exposure limit value for WBV. Furthermore, none of the cases with RP in the feet in our study reported any heredity for the condition among parents, siblings, or children. However, it is possible that the cases were not fully aware of their

Table 4. Assessment of foot-transmitted vibration for cases with Raynaud's phenomenon in the feet.

Case	Occupation	Vibration source	Vibration level (m/s^2)	Exposure duration (hours/day)	Cumulative exposure [m/s^2 A(8)]
I	Driller and loader	Drilling rig	0.2[a]	8	0.2
II	Vehicle operator	Haul truck	0.4[a]	8	0.4[c]
		Wheel loader	0.6[a]	8	0.6[c]
		Bulldozer	0.8[a]	8	0.8[c]
III	Mechanic and welder	Car	0.7[a]	2	0.4
IV	Production service technician	Car	0.7[a]	9	0.8[c]
		Haul truck	0.4[a]	4	0.4[c]
V	Support staff	Car	0.7[a]	2	0.4
VI	Support staff	-	-	-	-
VII	Crusher operator	Ore crusher	0.2[b]	8	0.2
VIII	Ore sampler	Car	0.7[a]	3	0.4
IX	Vehicle operator	Wheel loader	0.6[a]	6	0.5
X	Vehicle operator	Wheel loader	0.6[a]	5	0.5[c]
		Car	0.7[a]	5	0.6[c]
XI	Chef	-	-	-	-

[a]Dominant axis (x, y, or z) values including the k-factor (1.4) from on-site measurements on seats according to ISO 2631–1 using the HVM-100 instrument
[b]Reference value [5] since measurements were not performed.
[c]Different vibration sources and exposure duration depending on the workday.

Table 5. Clinical neurosensory examination results on the 11 cases that reported Raynaud's phenomenon in the feet.

	Right foot			Left foot		
Case	Vibration[a]	Pain[b]	Allodynia[c]	Vibration[a]	Pain[b]	Allodynia[c]
I	X		X	X		X
II			X			X
III	X	X	X	X	X	X
IV	X	X	X	X	X	X
V	X	X	X	X	X	X
VI		X	X		X	X
VII			X			X
VIII						
IX						
X				X		
XI	X			X		

X marks abnormal clinical findings.
[a]128 Hz tuning fork and/or VibraTip.
[b]Upholstery needle.
[c]Algometer.

relatives' potential symptoms. For primary RP affecting the hands, there are consistent findings in support of a hereditary component [35] and several candidate genes have been suggested [36]. The lack of a hereditary pattern and in our cases support that the condition was not of primary origin but rather acquired secondary to other aetiologies, as did the clinical findings suggestive of abnormal neurosensory function in the feet. Another important aspect to consider is ambient and contact cooling. Six of the cases with RP in the feet in our study worked in ambient cooling conditions for 1 to 6 hours per day and four had previously contracted local cold injuries. The cases with RP in the feet also reported more thermal discomfort in the toes in mild winter conditions compared to the ones without the condition. All vehicles did not have sufficiently heated driver's compartments and several cases had a mix of work tasks where they left the vehicles that they operated to work outdoors. Cold exposure works in synergy with vibration exposure to promote peripheral vasoconstriction [5,37]. In Annex D of ISO 5349–1, it is stated that climatic conditions and other factors that can affect the temperature of the hand or body should be considered in the risk assessment [38], and we argue that this reasoning should be applied also to the feet. The feet may actually be harder to protect than the hands, since they are continuously in contact with cold surfaces when standing or sitting, meaning that conductive heat loss can occur [39]. From a technical standpoint, it is challenging to develop boots that have sufficient thermal insulation to allow full days of outdoor work in the Arctic region [40]. For footwear used in the mining setting, emphasis is also put on blunt trauma protection (i.e. steel caps) and resilience to chemicals. Wearing heavy boots may also increase sweating and thus dampness of socks, which can enhance cooling of the feet. Finally, if boots get wet, they are not as easily replaced as gloves during the work shift.

Among the cases with RP in the feet, the majority also presented with clinical signs of neurosensory injury in the feet. Such findings have seldom been reported in the literature. Two of the previous case reports briefly addressed this issue [14,16] and a few previous studies on HAV-exposed workers have investigated neurosensory function in the lower extremities [19–21]. In one of these, it was shown that Japanese chainsaw operators with vibration-induced RP in the hands ($N = 19$) had reduced sensory nerve conduction velocities in the medial plantar nerve of the feet compared to age-matched controls [21]. These chainsaw operators were not exposed to FTV and the authors conclude that impaired nerve conduction velocities could reflect a distal neuropathy caused by a systemic vascular disturbance from recurring HAV exposure [21]. In a study on Finnish HAV-exposed chainsaw operators ($N = 109$), clinical examination revealed reduced perception of vibration in the feet in 39% and pain in 36% [19]. This can be compared to 55% with reduced vibration perception and 36% pain in our study (Table 5). Moreover, sensory nerve conduction velocities in the sural nerve were lower in Finnish chainsaw operators with neuropathic symptoms compared to asymptomatic individuals [19]. However, these Finnish chainsaw operators were also exposed to cold and wet conditions, which might have contributed to the development of neuropathic symptoms in the lower extremities. From the military setting, there are studies showing that cold winter conditions can affect neurosensory function in both the hands and feet, in the absence of any vibration exposure [41]. Thus, we find it plausible that a high occurrence of symptoms in the feet and toes among outdoor workers can also be due to wet and cold conditions in addition to exposure to HAV. To conclude, there is some evidence that neurosensory injury in the lower extremities can occur in vibration-exposed workers and this warrants attention in parallel with evaluation for vascular injury.

Pathophysiological mechanisms

Segmental exposure of the feet to vibration is believed to cause direct mechanical damage to peripheral vessels and nerves [5,17]. As an alternative or contributing mechanism, HAV exposure can promote a systemic vasoconstrictive response, which likely promotes the development of RP both in the hands and feet, even in the absence of direct vibration exposure of the feet [22,32]. This vibration-induced vasoconstrictive response is believed to be mediated by a general increase in sympathetic activity [42] and can involve increased circulating levels of noradrenalin [32] and endothelin [43], upregulation of specific adrenoceptors [44], as well as attenuation of acetylcholine-mediated vasodilation [45]. It has been convincingly demonstrated that short-term HAV exposure has immediate effects on the lower extremities, as assessed by skin temperature, cutaneous blood flow, sympathetic nerve activity, and perspiration [15,32,46]. It has also been shown that subjects with vibration-induced RP in the hands more often report coldness in the lower extremities [47] and show reduced tolerance to cold exposure, compared to unexposed subjects [31,32,46]. Thus, it is plausible that repeated vasoconstriction in the lower extremities as a consequence of a generalised HAV-induced sympathetic surge may contribute to more chronic circulatory disturbances of the feet [31].

Technical considerations

It is difficult to determine the appropriate technical means for assessing vibration exposure to the feet since a universally accepted specific measurement protocol is not yet available [48]. The standard for measurement of WBV (ISO 2631–1) was designed to encompass exposure to all surfaces supporting the body, including the feet [8]. It is based on the dominant axis of acceleration (x, y, *or* z) and employs a frequency weighting curve that attenuates higher frequencies that are likely to be of importance when assessing segmental effects in the feet [5]. Therefore, it is plausible that the use of this standard would underestimate the risks of vascular and neurosensory injury to the feet. In this context, it is interesting to note that all cases with RP in the feet in our study had cumulative exposure levels below the exposure limit value of 1.1 m/s^2 A(8) for WBV. Furthermore, the focus of WBV exposure assessment and risk prevention has traditionally been put on outcomes in the low back and not the lower extremities. Alternatively, the corresponding standard for HAV (ISO 5349–1) uses the vector sum of all three orthogonal axes (x, y, *and* z) and incorporates higher frequencies in the weighting curve [38]. However, this standard still likely underestimates the effects of high frequency and transient vibrations (i.e. impacts) and is based on transmission through the palm of the hand when gripping a tool. From an anatomical and functional standpoint, the feet show more resemblance with the hands than the spine, and this would support the use of the latter standard (ISO 5349–1) for risk assessment regarding injury to the feet. Another way to interpret vibration exposure is to analyse the frequency content in relation to resonance frequencies in the human body. For standing workers, lower frequencies (4 to 5 Hz) result in resonance in the pelvis and spine which can cause low back problems, while higher frequencies (40 to 50 Hz) are not propagated effectively further than the feet and thus may only have local effects in the feet [5,49]. Also, the resonant frequency range of the toes [50] closely resembles that of the fingers [51]. Finally, it is important to note that a worker can be exposed to vibration by several means at the same time. For instance, a driver of a vehicle can be exposed to HAV through the steering wheel, WBV through the seat and backrest, and FTV through the pedals and flooring [5]. While many studies describe exposure to HAV and WBV in the occupational setting, there are very limited data on FTV exposure. In future studies on vibration exposure, the scope should be widened and unfiltered data on FTV collected. In the long perspective, there might be a need for a separate standard for the assessment of FTV based on segmental, dynamic models [50,52] including footwear and posture [34,53].

Limitations and strengths

In our study, there were rather few cases that reported RP in the feet and the study was not sufficiently statistically powered to determine significant differences between cases and healthy subjects. The study was of cross-sectional design which means that time-relations could not be established. For instance, it cannot be ruled out that cases with RP in the feet had transferred from other lines of work to operating mining vehicles because of their symptoms (i.e. reverse causation). We also lacked more detailed information regarding RP in the feet, such as age of onset, anatomical distribution, and attack frequency. This means that we cannot fully determine if the condition was of primary or secondary origin, or to what extent vibration exposure contributed to the manifestation of symptoms. Thus, the study should be interpreted as hypotheses-generating rather than concluding on aetiologies for RP in the feet. The vibration measurements were conducted on the seat and not on the floor of the vehicles, and it is possible that the exposure magnitude at the feet was higher than at seat level since the latter is usually constructed to dampen vibration. Furthermore, we did not record the unfiltered vibration exposure. There are also some inherent strengths to our study. Instead of finding cases with a convenience sampling technique, we used a larger cohort of miners to establish the occurrence rate of the condition. We collected both survey data, performed clinical assessments by specialised physicians, and measured vibration levels in the vehicles that were used. Together, we believe that these data provide a broad perspective on the issue of RP in the feet.

Conclusions

The occurrence of RP in the feet of miners was 4.4%. Most cases with RP in the feet did not report the condition in the hands and were exposed to vibration transmitted directly to the feet. There were no reports of a hereditary component. Most cases with RP in the feet also had clinical findings suggestive of peripheral neuropathy in the feet.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Authors' contributions

AS, HP, and PV researched the literature, conceived the study, and formulated the aims. HP, AA, JW, and TN developed the protocol and collected the data. AA and TN performed clinical examinations. AS and HP aided in database construction and ACH performed data curation. AS performed data analyses and wrote the first draft of the manuscript. All authors reviewed and edited the manuscript and approved the final version.

Data availability statement

The dataset used during the current study can be made available upon reasonable request to the corresponding author.

ORCID

Albin Stjernbrandt http://orcid.org/0000-0001-6082-8465
Hans Pettersson http://orcid.org/0000-0001-7077-2389
Per Vihlborg http://orcid.org/0000-0002-4256-1880
Anje Christina Höper http://orcid.org/0000-0002-8962-5853
Jens Wahlström http://orcid.org/0000-0002-2359-509X
Tohr Nilsson http://orcid.org/0000-0003-2789-6321

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