Spike the PCHA! Overuse injury of the Posterior Circumflex Humeral Artery in elite volleyball
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CHAPTER 11

Summary
Conclusions
Clinical implications
Future research
11.1 – SUMMARY

In 1993, Reekers\textsuperscript{95} was the first to describe a traumatic aneurysm of the PCHA in a volleyball player, suggesting a causal relationship. Fifteen years later, between 2008 and 2010, several elite male volleyball players presented themselves in the Academic Medical Center (AMC) in Amsterdam with ischemic digits in the spiking hand due to arterial emboli originating from an aneurysmal and thrombosed posterior circumflex humeral artery (PCHA) in the dominant shoulder. At that time, just five case reports had been published worldwide on volleyball players with this injury.\textsuperscript{68,95,96,115,126} Knowledge about this sports-related overuse injury needs to be extended on an international scale considering the potential amputation of a finger as the devastating end result in a population of young, healthy and fit elite volleyball players. This is exemplified by the story of a 45-year-old retired Dutch volleyball player who contacted us after reading our first publication. When he was active at national top level in the 90s, he experienced severe complaints of coldness, discoloration, paresthesia and pain in several digits in his spiking hand for which no cause was found. Ultimately, the third digit in his spiking hand became necrotic and had to be amputated.

In this thesis, the first steps of elucidating the unexplored entity of Shoulder PCHA pathology and digital Ischemia in Known Elite volleyball players are made in order to provide an effective contribution to knowledge about this vascular overuse injury. In volleyball, spiking is the act of scoring a point by slamming the ball over the net into the opposing court effectively.\textsuperscript{130} Hence the title SPIKE the PCHA.

The first part of the thesis (PART I) covered our research on clinical characteristics like symptomatology and associated risk factors. PART II focused on research on optimal imaging strategies for detection and prevention. Combining new findings with conclusions from Part I and II generates suggestions for clinical management, discussed in PART III.

PART I – Symptomatology and associated risk factors
Athletes generally present themselves in an advanced stage of the disease with debilitating symptoms of digital ischemia in the spiking hand, like coldness, discoloration and paresthesia.\textsuperscript{58,95,96,115,126} These symptoms result in an inability to play volleyball and reduced daily quality of life. In an early stage of the disease, symptoms might only manifest after overhead movements in volleyball as a result of embolization into the digital circulation of the spiking hand. This can lead to a wide range of symptoms during or directly after volleyball. Similar symptoms will often be caused by, and attributed to, musculoskeletal injuries\textsuperscript{1}, and might therefore initially be perceived as minor, and thus ignored by the athlete. However, since there is a risk of necrosis and amputation, awareness of these symptoms, with a timely detection, is warranted.
The objectives of **chapter 2** were twofold. The first objective was to determine which symptoms are most likely to be associated with PCHA pathology (PCHAP) with distal embolization (DE) in the spiking hand in volleyball players. Using literature-based data on symptoms reported by volleyball players with confirmed digital ischemia as a result of PCHAP with DE, together with data retrieved from medical files of volleyball players treated for this injury, complaints of cold, blue and pale digits during or immediately after practice as well as competition were most strongly associated with DE as a result of PCHAP. Questions were formulated based on these symptoms of digital ischemia and included in the **Shoulder PCHA pathology and digital Ischemia - Questionnaire (SPI-Q)**. The second objective was to assess the prevalence of these symptoms in the spiking hand among elite male volleyball players in the Netherlands. Ninety-nine of 107 elite male volleyball players in the Netherlands completed the SPI-Q in a national survey in 2011: 91 indoor- and 8 beach volleyball players, a participation rate of 93%. An unexpectedly high percentage of 31% of these volleyball players reported symptoms of digital ischemia that are associated with PCHAP with DE in the spiking hand. These athletes are considered potentially at risk for developing critical digital ischemia since these symptoms might be the result of an early stage of the disease. Therefore further analysis of the presence of PCHAP and DE, and a better insight into modifiable risk factors to achieve effective prevention, is warranted.

In **chapter 3**, we assessed whether personal-, sports- and work-related risk factors are associated with self-reported symptoms of digital ischemia in the spiking hand. A national questionnaire survey in 2011 assessed the presence of symptoms and risk factors in 99 elite male volleyball players in the Netherlands: 91 indoor- and 8 beach volleyball players. Two sports-related risk factors were independently associated with symptoms of blue or pale digits in the spiking hand: a total volleyball career duration of 18 years or more (OR=6.70; 95%CI 1.12-29.54) and often or always performing weight training to increase dominant limb strength (OR=2.70; 95%CI 1.05-6.92). The identification of these sports-related risk factors is a first step in signalling and preventing apparently innocuous symptoms of digital ischemia.

The next step of implementation of the SPI-Q for periodic surveillance of elite volleyball players at risk for digital ischemia was to test its measurement properties. In **chapter 4**, the test-retest reliability of the SPI-Q was assessed with a two-week interval among 65 elite male indoor volleyball players, assessing symptoms of cold, pale and blue digits in the spiking hand during or after practice or competition. The results showed that the SPI-Q is a reliable questionnaire for: 1) detecting elite male indoor volleyball players with symptoms of digital ischemia in the spiking hand (kappa=0.83; 95%CI 0.69-0.97); and 2) for grading the severity of these symptoms (ICC=0.82; 95%CI 0.72–0.88). These findings indicate that the SPI-Q can be used for periodic surveillance of elite volleyball players.
Since the exposure to sport-specific demands is different in beach volleyball compared to indoor volleyball, the aim of chapter 5 was to assess the prevalence of ischemia-related symptoms in the spiking hand, and associated risk factors, among international world-class beach volleyball players. A questionnaire survey was performed during an international beach volleyball tournament in which 60 beach volleyball players participated: 26 males and 34 females from 17 countries, a participation rate of 49%. Thirty-eight percent of these volleyball players reported symptoms of digital ischemia that are associated with PCHAP with DE in the spiking hand. A total volleyball career duration of 14 years or more (OR=4.42; 90%CI 1.30-15.07), and sex (female) (OR=4.62; 90%CI 1.15-18.57) were independently associated with an increased risk of ischemia-related symptoms. Compared to elite indoor volleyball players assessed in chapters 2 and 3, the prevalence of symptoms of digital ischemia in the spiking hand was higher among elite beach volleyball players (38% versus 31%), and total volleyball career duration was a joint risk factor.

PART II – Imaging

In general, ultrasound (US) is the first-line imaging modality for peripheral aneurysm assessment. It is readily available, applicable on-site, inexpensive, patient friendly and enables non-invasive measurement of vessel diameters and detection of intravascular thrombus. Currently there is no standardized vascular US protocol available for imaging the PCHA. Such a protocol would enable worldwide uniform assessment of PCHA pathology. Moreover, given the complex local anatomy, including the frequently nearby originating and closely resembling deep brachial artery (DBA), evidence based recommendations and instructions for imaging would enable targeted PCHA identification and assessment.

In chapter 6, we present a 4-step standardized vascular US protocol for assessing the proximal PCHA: the Shoulder PCHA pathology and digital Ischemia – UltraSound (SPI-US) protocol. International standardization of PCHA imaging will help in accurate identification and assessment.

The next step in the development of the SPI-US protocol was to assess its measurement properties. In chapter 7, the inter-rater reliability of the SPI-US protocol for diameter assessment of the PCHA and DBA was assessed. Two vascular technologists independently determined diameters of the PCHA and DBA in 32 healthy volunteers using the SPI-US protocol. The results showed that the SPI-US protocol is accurate and precise for diameter assessment of the PCHA (ICC=0.70; 95%CI 0.50-0.83) and DBA (ICC=0.60; 95%CI 0.30-0.80), with sonographer-independent PCHA diameter measurements. Moreover, with a calculated Minimal Detectable Change (MDC) of 0.90 mm, the SPI-US seemed clinically valid for aneurysm detection when performed by experienced vascular technologists.
International dissemination of this protocol might make it possible to identify PCHA injury, both in an on-site screening setting, and in a clinical setting.

The objectives of chapter 8 were twofold. The first objective was to determine the prevalence of PCHA aneurysms in the dominant shoulder in elite volleyball players. The second objective was to describe PCHA and DBA anatomy, branching pattern, course and diameters. The SPI-US protocol was used to assess the PCHA and DBA in the dominant shoulder in 280 elite indoor and beach volleyball players, 245 men and 35 women. The PCHA was identified in 100% of the cases. Aneurysms were detected in the proximal PCHA in 4.6% (13/280) of elite volleyball players and associated with a specific branching type, namely a PCHA that originates directly from the axillary artery. The PCHA originated from the axillary artery (AA) in 81% of cases (228/280), and showed a curved course dorsally towards the humeral head in 93% of these cases (211/228), with a mean diameter of 3.8 mm (95%CI 3.7-3.9) in men, and 3.5 mm (95%CI 3.3-3.7) in women. The DBA was identified in 93% of cases (260/280), all without aneurysms. The DBA originated from the AA in 73% of cases (190/260), and showed a straight course parallel to the AA in 93% of these cases (177/190), with a mean diameter of 2.3 mm (95%CI 2.2-2.3) in men, and 2.0 mm (95%CI 1.9-2.2) in women. The described vessel characteristics and diameters provide clear guidance to identify and assess the PCHA and DBA using US. The high prevalence of detected PCHA aneurysms among elite volleyball players demands an active policy on prevention and periodic surveillance.

PART III – Clinical management

Increasing awareness among medical professionals through the dissemination of knowledge about this vascular injury will enable recognition, which is important to prevent the development of an advanced stage of the disease with serious ischemic complications. Invasive treatment options for PCHA aneurysms result in several months of rehabilitation and absence from volleyball activities. However, if PCHA pathology can be detected at an early stage, serious ischemic complications, irreversible tissue damage, and surgical ligation of the PCHA might be prevented. Since volleyball players are considered potentially at risk for developing critical digital ischemia in the spiking hand, analysis of the presence of PCHA pathology, and associated risk factors is warranted for prevention. Ultimately, establishing risk profiles of individual athletes would support clinical management.

The objectives of chapter 9 were fourfold: (1) to assess the prevalence of PCHA pathology in the dominant shoulder among elite volleyball players; (2) to determine its association with self-reported symptoms of digital ischemia in the spiking hand; (3) to assess possible personal- and sports-related risk factors, including dose-response relationship; and (4) to provide individual risk profiles for the clinical management of PCHA pathology based on prevalence, symptoms and associated risk factors. Two-hundred-seventy-eight
elite indoor- and beach volleyball players completed the SPI-Q assessing symptoms of digital ischemia and associated risk factors, prior to SPI-US screening for the presence of PCHA pathology, namely aneurysms, dilatations, and occlusions. PCHA pathology was detected in 17 participants (6.1%). In total, 96 of 278 participants reported symptoms associated with ischemic digits (35%) which were not associated with PCHA pathology (OR=0.39; 95%CI 0.13-1.13). A total volleyball career duration of 17 years or more and an age of 27 years or more were associated with a 9-fold (OR 9.21; 90%CI 1.61-52.63) and 14-fold (OR 13.61; 90%CI 2.43-76.40) increased risk of PCHA pathology, respectively.

Four risk profiles for elite volleyball players were formulated based on the combination of: (1) the presence of US-detected PCHA pathology (US+ or US−); and (2) symptoms of digital ischemia (Q+ or Q−); I) 1.1% US+Q+ (n=3), II) 5.0% US+Q− (n=14), III) 33.5% US−Q+ (n=93), and IV) 60.4% US−Q− (n=168). For each risk, profile recommendations for clinical management are proposed to optimize care for this potentially limb-threatening vascular overuse injury.

**Chapter 10** describes a case of a 34-year-old elite male volleyball player with symptomatic emboli in the spiking hand from a partially thrombosed aneurysm of the PCHA in his dominant shoulder. At 15-month follow-up after cessation of volleyball activities, digital blood pressure values almost normalized and a novel Magnetic Resonance Angiography (MRA) protocol showed an unchanged PCHA aneurysm and resolution of central filling defects in the digital arteries with post-thrombotic changes. This case report is the first to show promising results of conservative management as an alternative to more invasive treatment modalities for this vascular shoulder overuse injury.
11.2 – CONCLUSIONS

PART I – Symptomatology and associated risk factors (Chapters 2-5)
Among surveyed elite indoor- and beach volleyball players, symptoms of cold and discoloured digits in the spiking hand during or directly after practice or competition were prevalent in respectively 31% and 38% of the players. The duration of the volleyball career, the intensity of performing strength-increasing weight training, and the female sex were identified as associated risk factors (Table 1). These symptoms and risk factors for digital ischemia, which are associated with PCHA pathology, can be assessed adequately in an international arena using the Shoulder PCHA pathology and digital Ischemia – Questionnaire (SPI-Q): a reliable instrument for identifying elite volleyball players with symptoms of digital ischemia, and for grading the severity of these symptoms.

Table 1 Overview of the main outcomes of Chapters 2, 3, 5 (PART I), and 9 (PART III)

<table>
<thead>
<tr>
<th>Prevalence</th>
<th>Associated risk factors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Indoor volleyball:</td>
</tr>
<tr>
<td></td>
<td>volleyball career of ≥18 years*</td>
</tr>
<tr>
<td></td>
<td>frequency of strength-increasing exercises*</td>
</tr>
<tr>
<td>Symptoms of digital</td>
<td>35% 31% 23% 50%</td>
</tr>
<tr>
<td>ischemia</td>
<td>Indoor volleyball:</td>
</tr>
<tr>
<td></td>
<td>volleyball career of ≥14 years*</td>
</tr>
<tr>
<td></td>
<td>female sex</td>
</tr>
<tr>
<td></td>
<td>Beach volleyball:</td>
</tr>
<tr>
<td></td>
<td>volleyball career of ≥14 years*</td>
</tr>
<tr>
<td></td>
<td>female sex</td>
</tr>
<tr>
<td></td>
<td>age of ≥27 years*</td>
</tr>
<tr>
<td>PCHA pathology</td>
<td>6.1% 6.0% 7.7% 5.7%</td>
</tr>
<tr>
<td></td>
<td>volleyball career of ≥17 years*</td>
</tr>
</tbody>
</table>

* dose-response relation present

PART II – Imaging (Chapters 6-8)
The standardization of PCHA examination using the Shoulder PCHA pathology and digital Ischemia – Ultrasound (SPI-US) protocol, combined with detailed knowledge on PCHA and DBA vessel characteristics and diameters, enabled targeted, accurate and precise diameter measurements, as well as PCHA aneurysm detection (Table 2). Among the examined elite volleyball players, proximal PCHA aneurysms were prevalent in 4.6% and associated with a specific branching type, namely a PCHA that originates directly from the axillary artery.
### Table 2 Overview of the main outcomes of Chapters 7 and 8 (PART II)

<table>
<thead>
<tr>
<th></th>
<th>PCHA</th>
<th>DBA</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICC for diameter measurement</td>
<td>0.70 (95%CI 0.50-0.83)</td>
<td>0.60 (95%CI 0.30-0.80)</td>
</tr>
<tr>
<td>SEM</td>
<td>0.32 mm</td>
<td>0.29 mm</td>
</tr>
<tr>
<td>MDC</td>
<td>0.90 mm</td>
<td>0.80 mm</td>
</tr>
<tr>
<td>Presence of aneurysms</td>
<td>Yes (4.6% prevalence)</td>
<td>No</td>
</tr>
<tr>
<td>Presence of aneurysms in anatomical variants</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Location of aneurysms</td>
<td>Proximal (within 1.5 cm of origin)</td>
<td>n.a.</td>
</tr>
<tr>
<td>Presence in axillary pit</td>
<td>Always present</td>
<td>Commonly present (absent in 7% of cases)</td>
</tr>
<tr>
<td>Originating directly from the AA</td>
<td>81% of cases</td>
<td>75% of cases</td>
</tr>
<tr>
<td>Location of origin</td>
<td>Dorsal of the AA, proximal of the DBA</td>
<td>Dorsal of the AA, distal of the PCHA</td>
</tr>
<tr>
<td>Course at origin</td>
<td>Curved towards the dorsal side of the humerus</td>
<td>Straight and parallel to the AA</td>
</tr>
<tr>
<td>Intra-individual ratio</td>
<td>&gt;1.0 (PCHA dm / DBA dm)</td>
<td>&lt;1.0 (DBA dm / PCHA dm)</td>
</tr>
<tr>
<td>Average diameter (in mm)</td>
<td>3.8 (♂)</td>
<td>2.3 (♂)</td>
</tr>
<tr>
<td></td>
<td>3.5 (♀)</td>
<td>2.0 (♀)</td>
</tr>
<tr>
<td>Average diameter (corrected for BSA)</td>
<td>1.8 (♂)</td>
<td>1.1 (♂)</td>
</tr>
<tr>
<td></td>
<td>1.8 (♀)</td>
<td>1.1 (♀)</td>
</tr>
</tbody>
</table>

Key: ICC, intra-class correlation coefficient; SEM, standard error of measurement; MDC, minimal detectable change; AA, axillary artery; mm, millimeter; cm, centimeter; dm, diameter; ♂, men; ♀, women; BSA, body surface area; n.a., not applicable

**PART III – Clinical management (Chapters 9 and 10)**

To optimize care for this potentially limb-threatening vascular overuse injury, and to prevent serious ischemic complications in the spiking hand, clinical management recommendations for individual athletes have been formulated based on the combination of the presence or absence of PCHA pathology, associated risk factors, and reporting of symptoms of digital ischemia (Tables 1 and 3). Conservative management for a PCHA aneurysm with symptomatic emboli in the spiking hand showed promising results in one observed case.
### Table 3 Overview of the main outcomes of Chapter 9 (PART III)

<table>
<thead>
<tr>
<th>Prevalence</th>
<th>Recommendations for clinical management</th>
</tr>
</thead>
</table>
| US+Q+ 1.1% | * At risk for irreversible tissue damage from prolonged digital ischemia  
→ Refer to vascular surgeon for additional imaging and therapy |
| US+Q− 5.0% | * At risk for distal embolization from the aneurysmal PCHA  
→ SPI-US monitoring annually to identify progress of PCHA pathology  
Consult vascular surgeon in case of thrombus formation  
→ SPI-Q monitoring twice a year to detect onset of digital ischemia and to increase awareness  
Consult vascular surgeon when symptoms arise acutely or are associated with pulse deficits, pallor or differences in temperature between digits in the spiking hand |
| US−Q+ 33.5% | * Consider other causes of digital ischemia  
** At risk for PCHA pathology as the career progresses  
→ SPI-Q monitoring yearly to grade severity of digital ischemia and to increase awareness  
Consult vascular surgeon when symptoms aggravate acutely or are associated with pulse deficits, pallor or differences in temperature between digits in the spiking hand |
| US−Q− 60.4% | * At risk for PCHA pathology when symptoms of digital ischemia arise and as the career progresses  
→ SPI-US monitoring biannually to detect the onset of digital ischemia and to increase awareness  
Consult vascular surgeon when symptoms arise acutely or are associated with pulse deficits, pallor or differences in temperature between digits in the spiking hand |

Key: US+/−, presence or absence of PCHA pathology on SPI-US examination; Q+/−, presence or absence of symptoms of digital ischemia on SPI-Q surveillance
11.3 – CLINICAL IMPLICATIONS

Awareness
Aneurysmal degeneration, thrombosis and distal occlusion of the PCHA is a rare vascular shoulder overuse injury mostly found among elite volleyball players, and until a few years ago was not on the radar of volleyball players, national and international volleyball federations and medical professionals. To prevent serious ischemic complications, awareness of the existence of this injury is of vital importance. Through our research we have reached a large international population of elite beach- and indoor volleyball players, ranging from the Dutch under-18 squad to players at national and international top level. Hopefully these athletes now know not to trivialize apparently innocuous symptoms of digital ischemia in the spiking hand, and to seek timely medical attention. Also, we increased awareness through a systematic transfer of knowledge. Team physicians, (para)medical staff members, national and international sports medicine specialists, vascular technologists, radiologists, and the Fédération Internationale de Volleyball (FIVB) and the Dutch Volleyball Association (Nevobo) have been explicitly informed through our on-site research activities, promotional posts, presentations at medical conferences and practice sessions, website (www.spikestudy.com) and national and international publications in the field of sports medicine, occupational medicine, and radiology. In addition, as a result of national and international media attention generated by our first publications\textsuperscript{40,41}, more amateur volleyball players are aware of PCHA pathology and its concomitant symptoms. For example, a concerned mother from Chicago contacted us wondering if her 14-year-old son, who experienced cold hands during volleyball at an amateur level, was also at risk. As mentioned, a 45-year-old retired Dutch volleyball player contacted us. In the period that he was active at top national level in the 90s, he experienced severe complaints of ischemic digits in his spiking hand for which no cause was found. Ultimately, the third digit in his spiking hand became necrotic and had to be amputated. After reading our article, he recognized the described symptoms and contacted us with his story. This is a worst case example of how lack of awareness of this injury can lead to the loss of a finger. When the treating physician does not consider a proximal cause of signs and symptoms of digital ischemia in the spiking hand, imaging and therapy in the forearm and hand might be applied without treating the actual source of embolization, which might result in a postponed diagnosis and serious ischemic complications as a result of the recurrence of emboli. Hopefully, the international dissemination of this thesis, and its individual articles, will help prevent similar events in the future. We believe a key role in this process of spreading national and worldwide awareness through national volleyball federations and international volleyball tournaments lies with the FIVB.
Team physicians and sports medicine specialists

Knowledge about PCHA pathology and its concomitant symptoms should enable recognition, which is important for preventing serious ischemic complications. One in every 16 elite volleyball players (6.1%) has PCHA pathology in the dominant shoulder, a known source of digital embolization in the spiking arm in volleyball players, which is the equivalent of two players in every three volleyball teams. Therefore, sports physicians need to have a high index of suspicion when a volleyball player reports symptoms and signs of digital ischemia, especially as the volleyball career progresses. On the other hand, since one in every three elite volleyball players reports symptoms of digital ischemia in the spiking hand, and PCHA pathology was detected with ultrasound in only a small percentage of these athletes, sports physicians need to remain vigilant for other possible (vascular) causes. Two reliable standardized diagnostic instruments for assessing the PCHA and symptoms of digital ischemia, and clinical management recommendations on how to act based on the assessment outcomes, are provided and can be found on www.spikestudy.com. We encourage sports physicians to use these instruments and recommendations in daily practice. SPI-US assessment of the PCHA by sports medicine specialists might be possible, and even favourable, in the future, especially with the development of new smartphone ultrasound devices. Of course this should be accompanied by a comprehensive training in performing SPI-US examination given the fact that the reliability of the SPI-US protocol has only been assessed among experienced vascular technologists. Moreover, since PCHA pathology is often under-recognized and similar symptoms will often be caused by, and attributed to, musculoskeletal injuries, PCHA pathology in overhead sports should be addressed in the education of team physicians, sports medicine specialists, general practitioners, and orthopaedic- and vascular surgeons.

Vascular technologists and radiologists

Worldwide standardization of PCHA imaging will help in targeted and accurate identification and assessment. This thesis provides vascular technologists and radiologists with insights into how ultrasonography can be used for the surveillance of a vascular overuse injury which is prevalent in elite overhead athletes, like volleyball players. When confronted with an elite overhead athlete with symptoms of digital ischemia in whom only forearm and more distal vascular US is requested, proactive vascular sonographers should always consider a proximal cause of emboli and might therefore consider performing the standardized and reliable 5-10 minute SPI-US protocol to assess the PCHA for possible pathology. The four steps of the SPI-US protocol, including illustrative photographs combined with ultrasound images per step, can be found on www.spikestudy.com. We encourage vascular technologists and radiologists to use the SPI-US protocol. However, for targeted and accurate PCHA imaging, good anatomical knowledge of axillary artery branching patterns and its anatomic variations is essential. Moreover, to raise awareness and enable recognition, PCHA pathology in overhead sports should
be addressed in the education of vascular technologists and radiologists. An E-learning programme can play an important role in a timely international dissemination of the SPI-US protocol.

Prevention

The ultimate goal of sports medicine is to prevent injuries so that athletes remain competitive in the arena. According to van Mechelen’s model, the first step in the sequence of sports injury prevention research is to describe the magnitude of the problem in terms of frequency and severity of injuries. To do so, a comprehensive review of the medical literature was performed, which showed that PCHA pathology with serious ischemic complications is mostly reported among elite volleyball players. Also, multiple cases have been reported in elite baseball, tennis, swimming, kayaking, yoga, trapeze flying, American football, and even one in regular work, namely a mechanic.

The second step is to map the possible causes of injuries, and to identify their risk factors and mechanisms. According to the Bradford and Hill criteria for causation, a group of minimal conditions is necessary to provide adequate evidence of a causal relationship. This thesis has shown that the relationship between PCHA pathology and volleyball satisfies a number of these criteria, one of them being the strength (effect size) of the association. Case reports previously published on this topic were the first to indicate a causal relationship. Recently, a clear association has been demonstrated (see chapters 8 and 9), in which the prevalence of PCHA pathology among elite volleyball players has been objectified. Moreover, the presence of a time relationship and dose-response effect has also been demonstrated in chapter 9. Biological plausibility is provided by the fact that the vast majority of cases of PCHA pathology are found in sports that involve repetitive powerful overhead movements. The assumption is that these movements – for instance spiking and serving in volleyball and throwing in baseball – cause chronic vessel wall injury as a result of positional traction and compression of the proximal PCHA.

Lastly, the effect of exposure reduction is demonstrated in chapter 10, since cessation of volleyball activities resulted in the dissolution of intravascular thrombus as well as symptoms in the spiking arm and hand, and normalization of physical examination measurements as well as brachial artery and finger pressure measurements. Therefore, Reekers’ 1993 hypothesis seems to be confirmed in this thesis: PCHA pathology can be classified as a sports-related disease among volleyball players.

The final step in the injury prevention sequence, according to van Mechelen’s model, is to introduce measures that are likely to reduce the future risk and/or severity of sports injuries, and to document whether they are effective. At the moment, the literature on the prevention of PCHA pathology among volleyball players is lacking. A first step to introducing clinical management recommendations in order to prevent onset and worsening of PCHA pathology has been taken in chapter 9. The efficacy and feasibility of these and other yet to be introduced measures has to be evaluated in the future.
11.4 FUTURE RESEARCH

Future research into PCHA pathology among elite volleyball players should address at least the following five topics.

Firstly, the cause of unilateral ischemia-related symptoms in the spiking hand among the majority of volleyball players assessed in chapters 2, 3, 5 and 9 remains unknown. The high prevalence of these symptoms among professional athletes at the prime of their career is both unexpected and ominous. Therefore, future studies might address other serious vascular causes such as micro- and macrovascular damage in the fingers, hand, and forearm, which might be due to repeated vascular microtrauma by vigorous ball contact during passing, serving, spiking and blocking in volleyball. Moreover, the high prevalence among volleyball players emphasizes the need for surveillance of other overhead athletes at risk, such as baseball pitchers, to objectify the presence of symptoms of digital ischemia and assess associations with possible risk factors. The same goes for regular jobs with similar risk factors like mechanics and meat processing workers. Similar surveillance of young elite volleyball players might clarify the moment of onset of these symptoms and identify possible risk factors. Furthermore, a prospective assessment of symptoms of digital ischemia at regular intervals among elite volleyball players might reveal possible associations with both PCHA pathology and other causes.6,122

Secondly, the characteristics that predispose a volleyball player to develop PCHA pathology in the dominant shoulder remain unclear. One identified risk factor is the duration of the volleyball career, a variable which all volleyball players have in common. Additionally, based on the results of chapter 8, it seems that a PCHA originating directly from the axillary artery is another risk factor and that variant anatomy might be protective against PCHA pathology. However, the existence of more – still unknown – predisposing characteristics seems plausible. Although male sex was thought to be predisposing for PCHA injury among volleyball players, since the large majority of clinical cases have been reported in male volleyball players17, the prevalence of US-detected PCHA pathology was similar among men and women. Interestingly, female sex was a risk factor for symptoms of digital ischemia among beach volleyball players, which can be attributed to the notably high (50%) prevalence of these complaints in the spiking hand among female beach volleyball players, compared to their male colleagues (24%). Additionally, this prevalence was also much higher than among male indoor volleyball players (31%). Why women are more likely to perceive symptoms of digital ischemia in the spiking hand might be assessed in the future. However, a misleading impression might be provided since the group of participating female volleyball players in this thesis was relatively small. Therefore, it would be interesting for future studies to assess the presence of PCHA pathology, digital ischemia, and associated risk factors among elite female indoor- and beach volleyball players. Another example of a possible predisposing
characteristic is a familial predisposition for peripheral aneurysms, since these have been reported to be associated with genetic connective tissue disorders such as Marfan syndrome, Behçet disease, acromegaly and arteriomegaly.\textsuperscript{42,109} In this light it is worth noting that 15% (2/13) of volleyball players in this thesis in whom a PCHA aneurysm was detected reported the presence of aortic aneurysms in second-degree family members. For a better understanding of individual risk factors that predispose for PCHA pathology, prospective SPI-Q and SPI-US surveillance of volleyball players with asymptomatic PCHA pathology, starting with the 17 cases found in chapter 9, seems appropriate. Moreover, this might clarify the onset and course of symptoms in relation to the progress of PCHA pathology and the development of intravascular thrombus. Additionally, risk factors for similar injuries, such as symptomatic iliac artery compression in cyclists\textsuperscript{62,107}, might be examined for PCHA pathology among volleyball players. Furthermore, the AMC has a longstanding history in the field of medical research, for instance on wall shear stress in intracranial aneurysms. This knowledge might be useful for a better understanding of aneurysmal hemodynamics and intra-aneurysmal thrombus formation in the PCHA.

Thirdly, future studies should focus on preventive measures to prevent PCHA pathology in the dominant shoulder in elite volleyball players. Although only one case of a volleyball player has been described in whom cessation of volleyball activities led to the termination of symptoms and normalization of both physical examination and digital arterial blood pressure measurements (chapter 10), this observation gives rise to speculations concerning prevention. For instance, measures like limited amount of serves, spikes or overhead strength exercises per training session might be protective against PCHA overuse in the dominant shoulder. Moreover, since the intensity of performing strength-increasing weight training was found to be related to symptoms of digital ischemia, and might play a role in vascular overuse in the dominant shoulder, a better insight into biomechanical factors, like the type of movements and ranges of motion, and training characteristics, like intensity, frequency and duration, might be relevant for prevention. Furthermore, it might be interesting to explore the influence of the serve and spike technique on PCHA overuse in the dominant shoulder, with special attention being paid to the extreme shoulder angles achieved during these movements.

Fourthly, when diagnosed with PCHA pathology with symptomatic embolization in the spiking arm, elite volleyball players probably want to return to competition as soon as possible, and might therefore have a preference for invasive clinical modalities such as surgery or percutaneous interventional techniques. However, conservative management might be appropriate for a small percentage of these athletes. Therefore, future studies might assess the effect of conservative versus invasive clinical management using for instance interrupted time series studies\textsuperscript{106}, given the fact that the prevalence of clinical cases of volleyball players with PCHA pathology is low.
Fifthly, although the identification of the dose-response-related risk factors of volleyball career duration and age implies that chronic vessel wall overuse leads to the development of PCHA abnormalities, this has still to be confirmed in future studies.

In conclusion, although the first steps into the unexplored entity of PCHA pathology among elite volleyball players have been made in this thesis, plenty of territory remains uncharted, which provides a wide range of opportunities for future research.

Finally, the international dissemination of this thesis and its individual articles will encourage new research initiatives. We believe an important role in this process lies with the FIVB, and its collaboration with International Olympic Committee (IOC) accredited Research Centres, such as the Academic Center of Evidence based Sports medicine (ACES), which is part of the Amsterdam Collaboration on Health & Safety in Sports together with the VU University.

The mission of ACES as part of one of the nine worldwide expert centres for prevention of injury and protection of athlete health is the continuous improvement of health care for injured top-level athletes through integrated diagnostics, patient-tailored treatment and monitoring of treatment outcomes.

This is the first AMC thesis from this platform on which synergetic collaboration between experts in several clinical and preclinical disciplines, such as Orthopaedic surgery, Sports medicine, Human Movement Sciences and Radiology, fosters new insights and breakthrough research. This thesis is a prime example of how the ACES umbrella facilitates synergetic collaboration between medical professionals and students to perform scientific research through bachelor- and master thesis and PhD projects.