

Contributions of the Leukocyte Adherence Inhibition Test to the diagnosis of hypersensitivity reactions produced by nickel.

ABSTRACT

Aims: To evaluate the potential of the Leukocyte Adherence Inhibition Test (LAIT) as a diagnostic tool for nickel sensitization in patients with clinical suspicion of Nickel Hypersensitivity (NiH).

Study Design: We retrospectively examined the medical charts of a population of 102 patients diagnosed with chronic extensive dermatitis that prevented the employ of the diagnostic Patch Test and were investigated through an *ex vivo* challenge monitored by LAIT against NiSO₄(H₂O)₆.

Place and Duration of Study: Instituto Alergoimuno de Americana – São Paulo – Brazil – between January 2018 and May 2023.

Methodology Two groups were separated according to the patient's perception of pruritic reactions after prolonged contact with nickel alloys. Group A was composed of 45 patients denying pruritic reactions to prolonged contact with nickel alloys. Group B was composed of 57 patients that complained of local pruritic reactions produced by prolonged contact with nickel alloys. Cascade distribution charts were mounted with the range groups of Leukocyte Adherence Inhibition (LAI) results for visual comparison between the groups. The difference between the LAI means was studied with the help of the nonparametric Mann-Whitney U Test.

Results: The Cascade distribution charts showed a distinct distribution of LAI when comparing the two groups. This significative difference was supported by the Mann-Whitney U Test under $p < 0.01$.

Conclusion: Our preliminary results support the fact that the LAIT performed with NiSO₄(H₂O)₆ has the potential to become a diagnostic tool to help physicians to diagnose patients with NiH.

Keywords: Dermatitis, allergic contact; Dermatitis, contact; Diagnosis; Leukocyte Adherence Inhibition Test; Nickel; Skin tests.

1. INTRODUCTION

Nickel is a relatively nontoxic corrosion-resistant silver-white chemical element with the symbol Ni and atomic number 28 classified in the periodic table as a transition metal [1]. Nickel is a micronutrient bioavailable from the human diet [2]. Nickel is metabolically active and an essential trace element of the human body [3]. Nickel deficiency results in lower activities of several enzymes, affects carbohydrate metabolism, incorporation of calcium into bones, and iron absorption leading to anemia [4]. However, nickel toxicity may appear at large doses manifested as carcinogenicity, genotoxicity, haematotoxicity, teratogenicity, and immunotoxicity [5]. Used in metallurgy to forge Stainless Steel, nickel may contact human skin through earrings, body piercing, imitation jewelry (*bijou*), clothing accessories (buttons, belt buckles), razors, and occupational hazards [6]. Nickel Hypersensitivity (NiH) is one of the main responsible for Allergic Contact Dermatitis (ACD) in humans [7]. Nickel-related Allergic Contact Dermatitis (Ni-ACD) is a cutaneous hypersensitivity reaction developed after

prolonged skin contact with nickel alloys [8]. Haptens are collected from tegument by dendritic cells, which migrate to regional lymph nodes and present the hapten-peptide complexes to specific naïve T cells in an MHC-restricted fashion. The innate immune system is suggested to play a crucial role in Nickel sensitization through the Toll-like receptor 4 [9, 10]. The sensitized T lymphocytes return to the skin with the guidance of the cutaneous lymphocyte-associated antigen (CLA) [11]. Ni-ACD may be manifest exclusively at the site of the contactor or may be systemic, spreading far away from the contact point [12]. The systemic Ni-ACD is a differential diagnosis that overlaps the Intrinsic Atopic Dermatitis phenotype which may also be related to an increased serum nickel level [13]. Besides skin issues, NiH is also responsible for mucosal inflammation, which is named "Allergic Contact Mucositis" (ACM) which promotes oral and gastrointestinal symptoms in humans [14]. Nickel-related Allergic Contact Mucositis (Ni-ACM) produces a low-grade gastrointestinal inflammation manifested as an Irritable Bowel Syndrome-like gastrointestinal disorder, recurrent aphthosis, abdominal bloating, abdominal pain, diarrhea, constipation, nausea, vomiting, and endoscopic findings of chronic gastroduodenitis [15]. Ni-ACM also occurs with nickel contact with oral mucosa through Orthodontic Braces [16]. The systemic liberation of nickel and other metals from orthopedic prostheses is also a great concern [17]. NiH is related to systemic hypersensitivity, defined as the "Systemic Nickel Allergy Syndrome" (SNAS), a condition successfully treated with oral desensitization [18]. The SNAS is related to rhinitis, asthma, urticaria, angioedema, headache, chronic fatigue, post-prandial dyspnea, cystitis, vulvovaginitis, acne, and iron deficiency anemia [19]. Nickel-induced cellular damage may be minimized by nutritional interventions such as a low-nickel / antioxidant-rich / iron-sufficient diet. [20] N-acetylcysteine acts as an antioxidant to reduce oxidative stress, inflammation, and necroptosis caused by nickel exposure [21]. Nickel is present in the soil, drinking water, and in almost all dietary items, but foods usually high in nickel are: cocoa, soybeans, oatmeal, nuts, almonds, and legumes; however canned food may have a specially high nickel content liberated from the can alloy [22]. Nickel is not cumulative in the human body since it is easily eliminated by the kidneys. The main blood transport proteins are albumin and nickeloplasmin [23]. Historically, the most used method to clinically investigate the delayed hypersensitivity reactions responsible for ACD is the Patch Test [24]. The Patch Test is nowadays a medical procedure recommended under the guidelines of medical societies working for its standardization [25]. Nickel is one of the main etiologies for the delayed hypersensitivity reactions responsible for ACD as demonstrated by the Patch Test [26]. However, the results of a Nickel Patch Test are not always clinically relevant or reproducible, since the nickel may produce non-specific skin irritant reactions that may mislead the diagnosis of nickel sensitization [27]. The execution of the Patch Test also depends on the existence of an area of skin not affected by the disease, suitable for the placement of an adhesive patch containing the cameras with the studied allergens, which is usually done at the patient's back or the arms. However, sometimes, the patient does not have a sufficient area of uninjured skin to allow this procedure. Additionally, there is also a low risk of sensitization with this procedure [28]. These technical difficulties led some colleagues to search for a laboratory *ex vivo* methodology to diagnose immune sensitization in patients with NiH [29]. The inhibition of the cell migration was the first model for the demonstration of delayed hypersensitivity to an *ex vivo* allergen challenge [30]. This methodology was able to distinguish through *ex vivo* challenges performed with albumin-nickel conjugates patients with NiH from health controls [31]. The *ex vivo* stimulation of T lymphocytes of patients with NiH by nickel sulfate was amplified by the presence of macrophages [32]. Studies had shown that NiH is associated with a broad-spectrum T-cell cytokine response [33, 34]. The demonstration of this broad-spectrum cellular response to nickel has created new opportunities to *ex vivo* challenges in the diagnosis of NiH [35]. For 5 years, our Institute has employed *ex vivo* challenge tests monitored by the Leukocyte Adherence Inhibition Test (LAIT) as an alternative to the impossibility to perform a Nickel Patch Test due to the large extension of a patient's skin lesions [36]. The LAIT is a test similar to the Leukocyte Migration Inhibition Test, which exploits similar physiology but is easier to perform and standardize [37].

2. MATERIALS AND METHODS

2.1 Subjects

After receiving Institutional Review Board approval, from the Instituto Alergoimuno de Americana (Brazil), we proceed with the electronic chart review of a population of 7,200 allergic patients who

attended our outpatient facility from January 2018 to May 2023. A group of 102 patients had been submitted to an *ex vivo* allergen challenge test with nickel monitored with LAIT. This procedure was offered to the patient when indicated by the presence of extensive chronic dermatitis preventing the realization of a patch test. This was a very diversified cohort with 17 males; mean age 40.6 years; SD 20.4 years; range 1 to 82 years; modes = 29 years and 42 years (each appeared 6 times); geometric mean = 32.8 years. This group was divided into 2 groups according to the presence or the absence of the history of the subjects' perception of nickel contact dermatitis (such as cutaneous reactions to metal accessories such as earrings, piercings, metal cloth accessories, razors, bijou, *et cetera*). Group A was defined as the patients that did not perceive any reaction to the prolonged contact with nickel alloys. Group A had 45 participants, with 6 males; mean age 41 years; SD 20.4 years; range 5 to 73 years; mode = 42 years (appeared 4 times); geometric mean = 34.0 years. Group B was defined as the patients who complained of pruritic cutaneous reactions related to prolonged contact with nickel alloys. This a group with 57 participants, with 11 males; mean age 40.2 years; SD 20.3 years; range 1 to 82 years; mode = 29 years (appeared 4 times); geometric mean = 31.9 years.

2.2 Antigen preparation

The $[\text{NiSO}_4 (\text{H}_2\text{O})_6]$ was acquired from Labcenter Campinas. The powder was weighted and diluted in a buffer solution $[\text{NaCl } 10\text{g}; \text{KH}_2\text{PO}_4 \text{ } 0,72\text{g}; \text{Na}_3\text{PO}_4 \text{ } 2,86\text{g}; \text{H}_2\text{O } 600\text{mL}]$, to achieve the final concentration of 1 mg/mL to be employed in the LAIT.

2.3 *Ex vivo* Investigation: Leukocyte Adherence Inhibition Test

All patients were submitted to the *ex vivo* challenge tests monitored by the Leukocyte Adherence Inhibition Test (LAIT), against $\text{NiSO}_4 (\text{H}_2\text{O})_6$ to evaluate the cellular response. The LAIT was performed as previously described [38]. Shortly, each donor's fresh plasma was divided into two parts and used in paralleled *ex vivo* challenging tests with $\text{NiSO}_4 (\text{H}_2\text{O})_6$ and the unchallenged plasma assay. The plasma with high leukocyte content (buffy coat) was collected from the heparinized tube after one hour of sedimentation at 37 °C and aliquots of 100 μL were distributed into Eppendorf tubes kept under agitation for 30 minutes (200 rpm at 37 °C) with (or without, as used as control) antigen extract (10 μL of a solution with 1mg/mL and pH 7.5). After incubation, the plasma was allocated into a standard Neubauer hemocytometer counting chamber with a plain, non-metallic glass surface and left to stand for 2 hours at 37 °C in the humidified atmosphere of the covered water bath to allow leukocytes to adhere to the glass. Next, leukocytes were counted, the coverslip was removed, and the chamber was washed by immersion in a beaker with PBS at 37 °C. A drop of PBS was added to the hemocytometer's chamber and a clean coverslip was placed over it. The remaining cells were counted in the same squares as previously examined. The percentage of Leukocyte Adherence (LA) of each assay was estimated as: (the number of leukocytes observed on the hemocytometry chamber after washing divided by the number of leukocytes observed on the hemocytometry chamber before washing) and multiplied by 100 (%). The Leukocyte Adherence Ratio (LAR) was estimated based on the ratio between the LA from the antigen-specific challenged groups and the LA from the unchallenged control group: $\text{LAR} = \text{LA of the challenged sample divided by LA of unchallenged control sample; multiplied by } 100 (\%)$. To further calculate the Leukocyte Adherence Inhibition (LAI) the LAR was subtracted from 100 (%). The LAI results were further employed for the statistics calculations.

3. RESULTS

As a retrospective survey, there was no research protocol, therefore we report the incidental immune investigation as registered in the medical charts.

Group A results: The LAI mean was 34.3%; SD 28.9%; range 0% to 95%; mode = 0% (appeared 14 times).

Group B results: The LAI mean was 49.4%; SD 25.5%; range 0% to 97%; modes = 61% and 77% (each appeared 3 times).

The Mann-Whitney U Test Calculator resulted in the value of U as 880.5. The distribution was approximately normal. The Z-Score was 2.70591. The p-value was 0.00672 meaning a significant difference between the two nonparametric groups at $p < 0.01$.

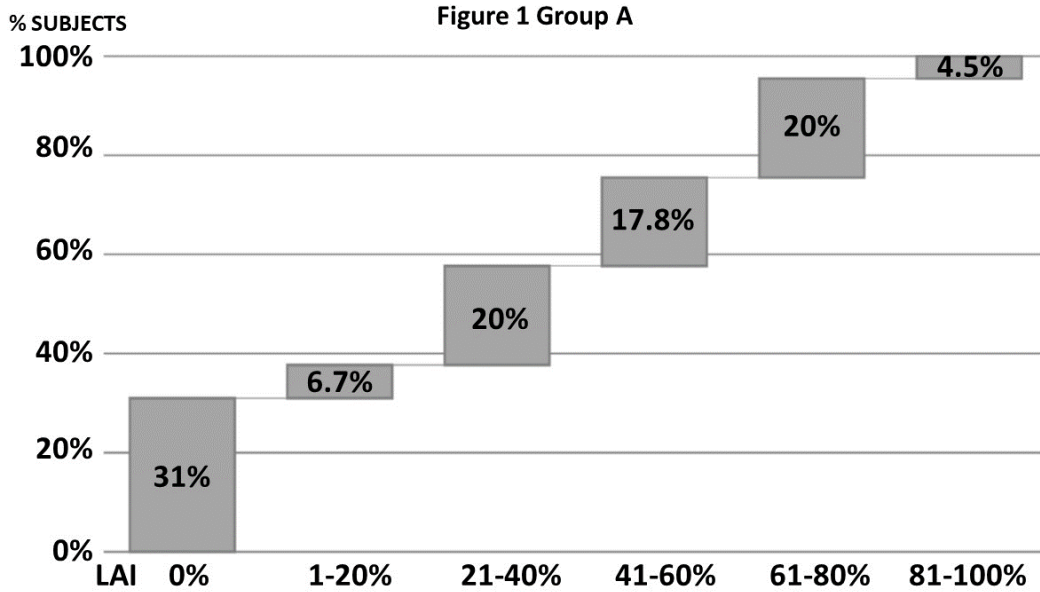


Fig. 1. Cascade distribution chart of the range groups of Leukocyte Adherence Inhibition results (x-axis %) of *ex vivo* NiSO₄ (H₂O)₆ challenges monitored by Leukocyte Adherence Inhibition Tests, according to the respective percentage of results over 45 tests (y-axis) performed on patients of group A (who did not report pruritic reactions to nickel alloys).

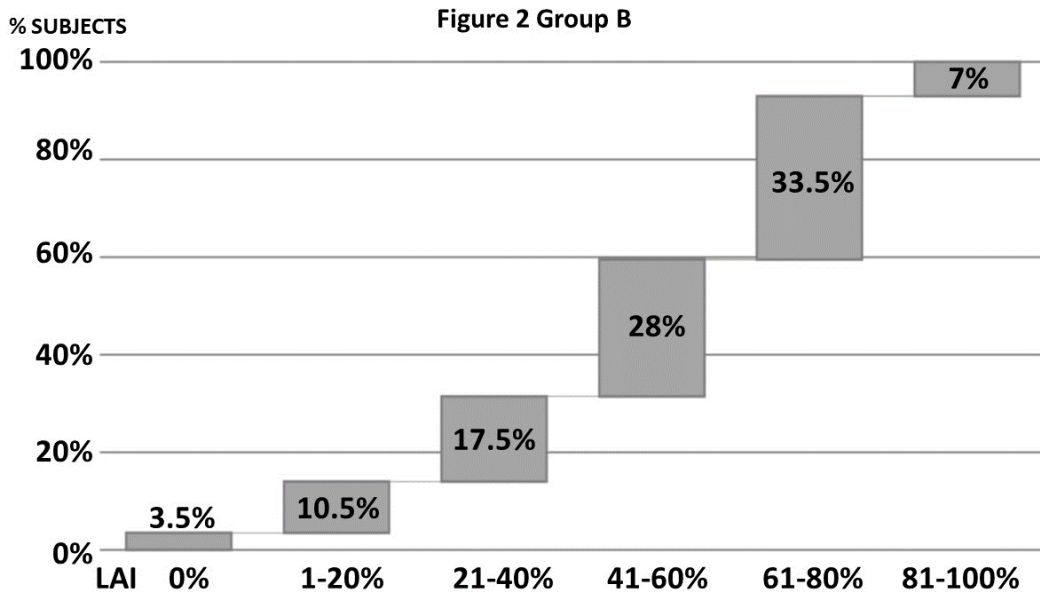


Fig. 2. . Cascade distribution chart of the range groups of Leukocyte Adherence Inhibition results (x-axis %) of *ex vivo* NiSO₄ (H₂O)₆ challenges monitored by Leukocyte Adherence Inhibition Tests, according to the respective percentage of results over 45 tests (y-axis) performed on patients of group B (who complained of pruritic reactions to nickel alloys).

4. DISCUSSION

Nickel is the most frequently positive allergen (19%) detected by the standard Patch Test battery of the North American Contact Dermatitis Group [38]. As a public health issue, medical societies are essaying efforts to promote the regulation of nickel use by the population [39]. Most of the knowledge about NiH is derived from murine studies demonstrating activation of CD8⁺ and CD4⁺ type 1 T cells which liberate proinflammatory cytokines, responsible for the apoptosis of keratinocytes. [40]. NiH is a lymphocyte-mediated Type IV Gell & Coombs delayed hypersensitivity reaction that occurs upon hapten-specific contact in sensitized individuals [41]. Haptens are low-molecular-weight sensitizers, able to be absorbed before to covalently bound to a protein (carrier) [42]. Nickel, usually is supposed to bind to proteins before being able to interact with immune cells to become a full antigen allowing antigen presentation and differentiation of T effector cells able to orchestrate hypersensitivity reactions [43]. However, it was already demonstrated that nickel reactivity may not be dependent on protein binding to activate antigen-presenting cells to stimulate the T cell receptor, at least to the HLA-DR–promiscuous VA22/VB17⁺ TCR human T cell clone SE9, acting in analogy with an idiotypic superantigen [44]. However, as a hapten, anything prevents the possibility of an assemblage of reaginic antibodies against the nickel-protein conjugate to produce humoral (immediate) responses too [36]. The LAIT is not a specific research tool to demonstrate any particular immune pathway, since several mechanisms may be involved in the inhibition of leukocyte adherence [45, 46]. LAIT is a triage test with a clinical utility to demonstrate the existence of some kind of immunoreactivity against a particular allergen [47]. Several immune mechanisms have been associated with LAIT [48]. Our preliminary retrospective survey has demonstrated that patients with NiH proved by the Patch Test also had LAIT positivity when challenged by NiSO₄ (H₂O)₆. Our retrospective study does not have information about the follow-up of the patients after the medical orientation to avoid nickel. More studies with prospective larger double-blind cohorts are in need to validate the hypothesis that the LAIT can potentially be used as a diagnostic tool to demonstrate NiH. We also need to consider that no *in vivo*, *ex vivo*, or *in vitro* positive test makes the diagnosis of “Allergy”. Allergy is a disease, clinically diagnosed by the assistant physician. These exams will demonstrate “sensitization” or “immunoreactivity”. They are just a “clue”. The confirmatory procedure is the *in vivo* Provocation Test. The *in vivo* provocation Test consists of the exclusion of the allergen, with a further re-introduction, which after remission of symptoms and further resurgence will prove causality between the allergen and the disease.

5. CONCLUSION

Our preliminary results support the fact that the LAIT performed with NiSO₄ (H₂O)₆ after further and more complete studies have the potential to become a diagnostic tool to help physicians to diagnose patients with NiH.

CONSENT

It is not applicable.

ETHICAL APPROVALS

As per international standards written ethical approval has been collected and preserved by the authors.

REFERENCES

- [1] H.A. Schroeder, J.J. Balassa, I.H. Tipton, Abnormal trace metals in man — nickel, *Journal of Chronic Diseases*, 15 (1962) 51-65.
- [2] N.W. Solomons, F. Viteri, T.R. Shuler, F.H. Nielsen, Bioavailability of Nickel in Man: Effects of Foods and Chemically-Defined Dietary Constituents on the Absorption of Inorganic Nickel, *The Journal of Nutrition*, 112 (1982) 39-50.
- [3] H.A. Schroeder, A.P. Nason, Trace-Element Analysis in Clinical Chemistry, *Clinical Chemistry*, 17 (1971) 461-474.
- [4] M. Anke, B. Groppel, H. Kronemann, M. Grün, Nickel - an essential element, IARC scientific publications, (1984) 339-365.
- [5] Z. Zdrojewicz, E. Popowicz, J. Winiarski, [Nickel - role in human organism and toxic effects], *Pol Merkur Lekarski*, 41 (2016) 115-118.
- [6] S.J.L. Linde, A. Franken, J.L. du Plessis, Skin and respiratory exposure to soluble lead, cobalt, nickel, copper, arsenic and silver at two South African precious metals refineries, *International archives of occupational and environmental health*, 96 (2023) 259-270.
- [7] T. Schäfer, E. Böhler, S. Ruhdorfer, L. Weigl, D. Wessner, B. Filipiak, H.E. Wichmann, J. Ring, Epidemiology of contact allergy in adults, *Allergy*, 56 (2001) 1192-1196.
- [8] M.G. Ahlström, J.P. Thyssen, M. Wennervaldt, T. Menné, J.D. Johansen, Nickel allergy and allergic contact dermatitis: A clinical review of immunology, epidemiology, exposure, and treatment, *Contact Dermatitis*, 81 (2019) 227-241.
- [9] M. Schmidt, B. Raghavan, V. Müller, T. Vogl, G. Fejer, S. Tchaptchet, S. Keck, C. Kalis, P.J. Nielsen, C. Galanos, J. Roth, A. Skerra, S.F. Martin, M.A. Freudenberg, M. Goebeler, Crucial role for human Toll-like receptor 4 in the development of contact allergy to nickel, *Nat Immunol*, 11 (2010) 814-819.
- [10] B. Roediger, W. Weninger, How nickel turns on innate immune cells, *Immunol Cell Biol*, 89 (2011) 1-2.
- [11] A. Cavani, D. Mei, E. Guerra, S. Corinti, M. Giani, L. Pirrotta, P. Puddu, G. Girolomoni, Patients with allergic contact dermatitis to nickel and nonallergic individuals display different nickel-specific T cell responses. Evidence for the presence of effector CD8+ and regulatory CD4+ T cells, *J Invest Dermatol*, 111 (1998) 621-628.
- [12] C. Matiz, S.E. Jacob, Systemic contact dermatitis in children: how an avoidance diet can make a difference, *Pediatr Dermatol*, 28 368-374.
- [13] H. Yamaguchi, N. Hirasawa, S. Asakawa, K. Okita, Y. Tokura, Intrinsic atopic dermatitis shows high serum nickel concentration, *Allergol Int.* 2015 Jul;64(3):282-4. doi: 10.1016/j.allit.2015.01.003. Epub 2015 Feb 12. 2015.
- [14] N. Greco, A. Pisano, L. Mezzatesta, M. Pettinelli, A. Meacci, M.G. Pignataro, C. Giordano, A. Picarelli, New Insights and Evidence on "Food Intolerances": Non-Celiac Gluten Sensitivity and Nickel Allergic Contact Mucositis, 15 (2023) 2353.
- [15] R. Borghini, M. Puzzone, E. Rosato, M. Di Tola, M. Marino, F. Greco, A. Picarelli, Nickel-Related Intestinal Mucositis in IBS-Like Patients: Laser Doppler Perfusion Imaging and Oral Mucosa Patch Test in Use, *Biological Trace Element Research*, 173 (2016) 55-61.
- [16] C.W. Stewart, C.M. Hammond, M.S. Godat, D.B. Lew, Delayed Severe Gingivitis After Placement of Orthodontic Braces in an Atopic Teenager: A Case Report and Literature Review, *Pediatr Allergy Immunol Pulmonol*, (2023).
- [17] J. Vilaplana, C. Romaguera, F. Grimalt, R. Ramón Soler, J. Gallart Castany, M.I. Rodamilans Pérez, J. To Figueras, [Nickel, chromium and cobalt release from a metal prosthesis in metal-sensitive patients], *Medicina cutanea ibero-latino-americana*, 17 (1989) 405-408.

- [18] L. Ricciardi, A. Carni, G. Loschiavo, S. Gangemi, V. Tigano, E. Arena, C. Mannucci, G. Calapai, Systemic nickel allergy: oral desensitization and possible role of cytokines interleukins 2 and 10, *Int J Immunopathol Pharmacol*, 26 (2013) 251-257.
- [19] L. Ricciardi, A. Arena, E. Arena, M. Zambito, A. Ingrassia, G. Valenti, G. Loschiavo, A. D'Angelo, S. Saitta, Systemic nickel allergy syndrome: epidemiological data from four Italian allergy units, *Int J Immunopathol Pharmacol*, 27 (2014) 131-136.
- [20] D. Filatova, C. Cherpak, Mechanisms of Nickel-Induced Cell Damage in Allergic Contact Dermatitis and Nutritional Intervention Strategies, *Endocrine, metabolic & immune disorders drug targets*, 20 (2020) 1010-1014.
- [21] X. Zhang, L. Xu, W. Ma, B. Shi, Q. Liu, Y. Song, C. Fang, P. Liu, S. Qiao, J. Cai, Z. Zhang, N-acetyl-L-cysteine alleviated the oxidative stress-induced inflammation and necroptosis caused by excessive NiCl₂ in primary spleen lymphocytes, *Front Immunol*, 14 (2023) 1146645.
- [22] A.D. Sharma, Low nickel diet in dermatology, *Indian J Dermatol*, 58 (2013) 240.
- [23] D.G. Barceloux, Nickel, *J Toxicol Clin Toxicol*, 37 (1999) 239-258.
- [24] J.M. Lachapelle, [Patch testing: historical aspects], *Ann Dermatol Venereol*, 136 (2009) 575-577.
- [25] J.D. Johansen, K. Aalto-Korte, T. Agner, K.E. Andersen, A. Bircher, M. Bruze, A. Cannavó, A. Giménez-Arnau, M. Gonçalo, A. Goossens, S.M. John, C. Lidén, M. Lindberg, V. Mahler, M. Matura, T. Rustemeyer, J. Serup, R. Spiewak, J.P. Thyssen, M. Vigan, I.R. White, M. Wilkinson, W. Uter, European Society of Contact Dermatitis guideline for diagnostic patch testing – recommendations on best practice, *Contact Dermatitis*, 73 (2015) 195-221.
- [26] B. Roque Quintana, A. Falcón Hernández, A. Sagraera Guedes, L. Borrego, Contact Dermatitis to Allergens in the Spanish Standard Series: Patch Test Findings in the South of Gran Canaria, *Actas Dermosifiliogr*, 113 (2022) 555-562.
- [27] C.G. Mortz, H.F. Kjaer, E. Eller, M. Osterballe, L.A. Norberg, A. Høst, C. Bindslev-Jensen, K.E. Andersen, Positive nickel patch tests in infants are of low clinical relevance and rarely reproducible, *Pediatr Allergy Immunol*, 24 (2013) 84-87.
- [28] C.D. Jensen, E. Paulsen, K.E. Andersen, Retrospective evaluation of the consequence of alleged patch test sensitization, *Contact Dermatitis*, 55 (2006) 30-35.
- [29] B. Nordqvist, H. Rorsman, Leucocytic migration in vitro as an indicator of allergy in eczematous contact dermatitis, *Trans St Johns Hosp Dermatol Soc*, 53 (1967) 154-159.
- [30] M. George, J.H. Vaughan, In vitro cell migration as a model for delayed hypersensitivity, *Proc Soc Exp Biol Med*, 111 (1962) 514-521.
- [31] A.M. Mirza, M.G. Perera, C.A. Maccia, O.G. Dziubynskyj, I.L. Bernstein, Leukocyte Migration Inhibition in Nickel Dermatitis, *International Archives of Allergy and Applied Immunology*, 49 (2009) 782-788.
- [32] S. Silvennoinen-Kassinen, Lymphocyte Transformation in Nickel Allergy: Amplification of T-lymphocyte Responses to Nickel Sulphate by Macrophages in Vitro, *Scandinavian Journal of Immunology*, 12 (1980) 61-65.
- [33] N.P.J. De Graaf, S. Roffel, S. Gibbs, C.J. Kleverlaan, M. Lopez Gonzalez, T. Rustemeyer, A.J. Feilzer, H.J. Bontkes, Nickel allergy is associated with a broad spectrum cytokine response, *Contact Dermatitis*, 88 (2023) 10-17.
- [34] B. Dyring-Andersen, L. Skov, M.B. Løvendorf, M. Bzorek, K. Søndergaard, J.-P.H. Lauritsen, S. Dabelsteen, C. Geisler, C. Menné Bonefeld, CD4⁺ T cells producing interleukin (IL)-17, IL-22 and interferon- γ are major effector T cells in nickel allergy, *Contact Dermatitis*, 68 (2013) 339-347.
- [35] A. Popple, J. Williams, G. Maxwell, N. Gellatly, R.J. Dearman, I. Kimber, The lymphocyte transformation test in allergic contact dermatitis: New opportunities, *Journal of Immunotoxicology*, 13 (2016) 84-91.
- [36] D.L. Morris, Intradermal testing and sublingual desensitization for nickel, *Cutis*, 61 (1998) 129-132.

- [37] A.W. Bullen, M.S. Losowsky, Comparison of a leucocyte adherence test with the leucocyte migration inhibition test and skin reactivity to PPD, *Clin Exp Immunol*, 31 (1978) 408-413.
- [38] K.A. Zug, E.M. Warshaw, J.F. Fowler, Jr., H.I. Maibach, D.L. Belsito, M.D. Pratt, D. Sasseville, F.J. Storrs, J.S. Taylor, C.G. Mathias, V.A. Deleo, R.L. Rietschel, J. Marks, Patch-test results of the North American Contact Dermatitis Group 2005-2006, *Dermatitis: contact, atopic, occupational, drug*, 20 (2009) 149-160.
- [39] M.G. Ahlström, M. Wennervaldt, G. McCombie, P. Blaser, C. Lidén, Regulatory action needed to combat nickel contact allergy in the population, *Contact Dermatitis*, 89 (2023) 77-78.
- [40] A. Cavani, *Immune Mechanisms in Allergic Contact Dermatitis*, CRC Press 2005.
- [41] P.G.H. Gell, R.R.A. Coombs, Classification of Allergic Reactions Responsible for Clinical Hypersensitivity and Disease., in: P.G.H. Gell, R.R.A. Coombs (Eds.) *Clinical Aspects of Immunology*, Blackwell Scientific Publications, Oxford, 1968, pp. 575-596.
- [42] D.H. Katz, J.M. Davie, W.E. Paul, B. Benacerraf, Carrier function in anti-hapten antibody responses. IV. Experimental conditions for the induction of hapten-specific tolerance or for the stimulation of anti-hapten anamnestic responses by "nonimmunogenic" hapten-polypeptide conjugates, *J Exp Med*, 134 (1971) 201-223.
- [43] A. Schwarz, R. Philippsen, T. Schwarz, Mouse Models of Allergic Contact Dermatitis: Practical Aspects, *J Invest Dermatol*, 143 (2023) 888-892.
- [44] K. Gamerding, C. Moulon, D.R. Karp, J. van Bergen, F. Koning, D. Wild, U. Pflugfelder, H.U. Weltzien, A New Type of Metal Recognition by Human T Cells: Contact Residues for Peptide-independent Bridging of T Cell Receptor and Major Histocompatibility Complex by Nickel, *Journal of Experimental Medicine*, 197 (2003) 1345-1353.
- [45] D.M.P. Thomson, *Assessment of immune status by the leukocyte adherence inhibition test*, Academic Press, New York, 1982.
- [46] A.W. Tong, D.R. Burger, P. Finke, C. Barney, A.A. Vandebark, R.M. Vetto, Assessment of the mechanism of the leukocyte adherence inhibition test, *Cancer Res*, 39 (1979) 597-603.
- [47] A. Fink, L. Heller, A. Eliraz, Z. Weisman, A. Miskin, M. Schlezinger, H. Bibi, Z. Bentwich, Allergen-specific leukocyte adherence inhibition (LAI) assay: sensitivity, specificity and mechanism, *Immunol Lett*, 16 (1987) 65-70.
- [48] W.J. Halliday, A. Maluish, S. Miller, Blocking and unblocking of cell-mediated anti-tumor immunity in mice, as detected by the leukocyte adherence inhibition test, *Cellular Immunology*, 10 (1974) 467-475.