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Review article

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Ceramic-related noise as an adverse outcome in total hip arthroplasty

B.R. Tashtanov[1]✉, I.A. Kirilova[1], D.V. Pavlova[2], V.V. Pavlov[1]

[1] Novosibirsk Research Institute of Traumatology and Orthopedics n.a. Ya.L. Tsivyan, Novosibirsk, Russian Federation
[2] Novosibirsk State Medical University, Novosibirsk, Russian Federation

Corresponding author: Baikozho R. Tashtanov, b.tashtanov95@gmail.com

Abstract

Introduction Ceramic hip replacement bearings have shown to be low wearing and biocompatible. The last two generations of Biolox Forte and Biolox Delta ceramics have have established themselves as durable bearings. However, squeaking and noise from ceramic bearing THRs is well recognised in the 21st century. **The objective** was to explore the problem of noise in the ceramic bearing of THA based on the analysis of the foreign and Russian literature. **Material and methods** In presented the analysis of Foreign and Russian literature searches for the review were produced according to PRISMA recommendations using PubMed, Scopus, Google Scholar, eLibrary. MINOR was used to assess the methodological quality of articles. **Results and Discussion** Noise in ceramics is observed in 37.7 %. There are many theories on the origin and mechanism of noise including liner impingement and loading, film disruption, third body, microseparation and resonance. However, there is still no consensus on what is noise in the ceramic bearing and how to solve this problem. **Conclusion** Literature review of ceramic bearing indicated enough unanswered questions. The noise may play a role as a predictor of improper use of endoprosthesis with accumulated database resulting in better understanding of the phenomenon, methods of the correction and timely prevention of ceramic breakage.

Keywords: total hip arthroplasty, ceramic bearing, noise in ceramics, squeaking in ceramics

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INTRODUCTION

Total hip arthroplasty (THA) has been quoted as one of the most successful and cost-effective procedures in orthopaedics and can be used in patients aged 18-30 years [1]. A major long-term problem affecting THA survivorship is polyethylene wear and the resultant wear-induced osteolysis [2, 3]. Ceramic-on-ceramic hip bearings were first introduced by P. Boutin in 1971 with a first implantation of ceramic components from CeramTec in 1975 [4]. The first models of this pair were rejected by surgeons due to their fragility, and in 1993 the 3rd generation Biolox Forte was developed [5]. Although medium-term results of using theceramic were reported as good, the complication rate in the form of squeaking hips remained high [6]. Fourth generation ceramics made of alumina-zirconia composite followed by addition of 18 % zirconium dioxide, 1 % strontium oxide, 1 % chromium oxide was developed in 2003 [7]. The modern ceramics are described as a bioinert and wear-resistant material [8, 9]. The Biolox Delta generation showed excellent performance at a mid term [10, 11]. The fracture of ceramic heads decreased significantly [10, 12], and the fracture of the liner amounted to 0.03 % [13]. In percentage terms, the results may seem clinically insignificant, but the consequences of ceramic breakage are catastrophic [9, 11] because destroyed ceramic components are not recommended to be replaced with less fragile materials due to the fact that ceramic debris and the third body remaining in the surrounding soft tissues as a result of a fracture can penetrate into the friction surface and destroy it if it is softer than ceramics [11, 14, 15]. Before 2005, squeaking was not recognized as a clinically important complication of ceramic bearings [6]. Patient demands have increased with intention for an artificial joint feeling much more like the patient's natural hip [16]. Many factors have been described that provoke noise in a ceramic pair, but the complication can develop with well aligned prosthetic components [17, 18] that is associated with the quality of life of patients [18]. Owen D.H. et al. reported the incidence of revision for squeaking of 0.2 % [19]. Therefore, squeaking has become an unanticipated clinical outcome and an adverse event of the 21st century in THA [6].

The objective was to assess the problem of squeaking in the ceramic friction pair of THA based on an analysis of foreign and Russian literature.

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MATERIAL AND METHODS

This review was conducted in accordance with PRISMA guidelines [20]. The search was performed using open electronic databases of PubMed, Scopus, Google Scholar, eLibrary and keywords and phrases: ceramic bearing[Title/Abstract] or ceramic on ceramic [Title/Abstract] or ceramic squeaking [Title/Abstract]) and hip[Title/Abstract] in English databases and ceramics, squeaking, endoprosthetics in the Russian-language database. The literature was reviewed by two independent reviewers: the first stage included screening by title and abstract. The search depth was 20 years until 2002. Inclusion criteria: literature of any level of evidence, full text in Russian and English freely available, focused on squeaking of the ceramic friction pair of THA. Exclusion criteria included reviews, expert opinions, book chapters, conference abstracts, case reports and studies in Russian and English. Studies with follow-up of less than 5 years. The second stage included an analysis of the full texts of the relevant studies. The methodological quality of articles was assessed using MINOR (Methodological Index for Nonrandomized Studies) [21].

RESULTS AND DISCUSSION

The results of a literature analysis showed that squeaking in ceramics can occur in 36 % [22-26]. The frequency of squeaking in 3rd generation ceramics was 2.4 % [27]. Squeaking statistics averaged 3 % in a recent meta-analysis of 4th generation ceramics [28]. Many causes for squeaking have been reported and the complication appeared to be a multifactorial problem [6, 29]. The factors were classified into three categories: surgical, patient-related, and implant-related [6].

Surgical factors

Incorrect positioning of components. Patients who complain squeaking in THA have excessive or insufficient anteversion or inclination of components over 45 degrees [22, 25, 28, 30-32]. In contrast, other studies have not found a similar relationship with acetabular component orientation [27, 33-36]. Medialization or lateralization of the center of rotation of the acetabulum, according to F. Castagnini and S. Sexton, also contributes to the genesis of squeaking, disrupting the contact patch [29, 31, 37].

A *loosely fitted liner* has not only a high risk of squeaking in the prosthetic joint, but also the risk of early destruction due to micromobility between the surfaces of the liner and the acetabular component, resulting in the formation of a second friction pair between the liner and the cup [6, 35]. The reason for the early failure of ceramics in the form of chips after THA may be a situation that was demonstrated in laboratory conditions, with loosely fitted liners being more susceptible to squeaking than tightly fitted liners [38].

Screws. The acetabular screws may come into contact with the rear surface of the liner with extrusion and cause either noise or microcracks in the liner [39-41].

Patient-related factors

Age. Young, tall, and active patients are more susceptible to squeaking [29]. Siddhard M.S. et al. reported a statistically significant difference in age between patients with and without squeaking in a prospective cohort study [22]. The authors suggested the correlation between greater activity and physical performance in young people.

BMI. Walter W.L. suggested that demographic data indicated to squeaking being more likely in patients with greater weight and height [6, 27]. Patients weighing more than 91 kg were 4.76 times more likely to have ceramic fractures than patients weighing less [42, 43].

Gender. Choi I.Y. et al. reported gender as a factor influencing the occurrence of squeaking. The study suggested that men were more susceptible to squeaking due to greater physical activity [36, 44].

Concomitant pathologies of the lower extremities. Limb length discrepancy can be assessed with complications such as muscle imbalance, impingement, dislocation and displacement of the contact patch. McDonnell S.M. et al. suggested that squeaking was more common in patients with excessive range of motion, which was associated with muscle imbalance [23]. Excessive motion can lead to microseparation or rim loading being the underlying mechanism for squeaking [23, 45]. McDonnell S.M. reported that muscle atrophy and a wide range of motion significantly increased the risk of squeaking [23]. Rheumatoid arthritis can be a risk factor for squeaking, although the association was difficult to explain [46].

Consequences of fractures of ceramic components. A major problem includes the spread of small sharp ceramic particles into soft tissues as a result of fracture, that cannot be removed during revision [47, 48]. The consequences of fractured ceramic components would also affect subsequent implantation of prostheses in the form of a third body effect [49, 50]. In contrast to the above studies, Keurentjes J.C. and Restrepo C. reported no correlation between squeaking and the above factors [34, 35].

Implant-related factors

Component size. Component size in a ceramic friction pair do not increase wear [51]. Many authors have recommended the use of larger heads to reduce the risk of dislocation by increasing the vault distance. Recent studies have shown a higher risk of squeaking with larger sizes of friction pair components [18, 44] which can increase the risk of cleavage. The first five-year results of the Australian registry showed that the revision rate of THA with larger heads was not less than the of revision rate with 32-size heads [52]. Thomas et al. reported the squeaking rate of 13.5 % with 36 mm heads and 5.9 % with 28 mm heads in a comparative prospective study, and suggested that head size was the only predictor had no effect on outcome, but only in combination with several other factors (predictors) [53]. Larger heads can increase the rim pressure on the liner when the cup is placed more vertically, creating the potential for squeaking. The dimensions of the components can increase the mass of the implant reducing the natural frequency of component vibrations, increasing the amplitude and enhancing the initial vibration leading to squeaking [18].

Differences between technological manufacturing assembly and manual intraoperative assembly. The incidence of squeaking in the group of the factory-assembled Delta Motion cup was significantly higher compared to the ceramic friction pairs assembled intraoperatively [28]. The use of Pressfit Delta Motion cups increased the frequency of squeaking. This could happen due to the fact that the pelvic component could not be fixed with screws causing loosening of the pelvic component and changing the components position. Parvizi J. suggested that cups with a high rim were more susceptible to squeaking when the rim of the ceramic liner was higher than the rim of the cup [54]. Stanat S.J. reported no association between squeaking and higher rim of ceramic liners in the meta-analysis [27].

Design features of the femoral component (offset and neck thickness). Swanson T.V. and Wu G.L. reported Stryker Accolades being more susceptible to squeaking due to the short neck and offset of the femoral component [46, 55, 56]. Thick necks were more susceptible to impingement on the rim of the liner, with a 28 mm femoral head, in particular. Kim H.S. et al. reported the collision statistics of 10 %, which was extremely high for ceramics. No liner fractures were reported in the impingement group at 10 year follow-up, with 21 out of 27 "squeaking" prostheses having a 28 mm head and a thick neck of the femoral component [57]. A study was also conducted to determine the relationship between squeaking and implant models and manufacturers. "Stryker Accolade" and "De puy Summit" were the most 'squeaking' endoprostheses due to tapered proximal portion "Müller" and the philosophy of proximal fixation [27, 28, 46]. Several studies reported that the squeaking could be associated with low-profile femoral components and a thin neck [17, 33, 34]. Fan N. et al. conducted an *in vitro* study and demonstrated that stiffer and shorter femoral components had a higher critical coefficient of friction, which correlated with clinical data [58]. Lee T.H. reported the meta-analysis which included 132 studies on squeaking with the only significant factor being the angle of inclination of the acetabular component [59].

Component materials. Loosening of the femoral component can produce an abrasive and impair lubrication properties of the friction pair causing squeaking [54, 60]. The authors reported that the Stryker Accolade had a more flexible structure, that resulted in better pain relief [56]. The implant had greater potential for resonance due to the flexibility [28, 56]. Restrepo C. et al. suggested that the metal alloy of the endoprosthesis could affect squeaking due to differences in vibration conductivity [56].

Pathogenesis of squeaking in ceramics

Theories about the mechanism of noise vary. Some studies indicate that the noise is a consequence of abnormal friction. Others hypothesize resonance of components during normal friction [61, 62].

Impingement and stress on the rim of the liner. The noise may be a product of the neck of the femoral component impinging on the ceramic rim of the liner. Third bodies can also cause impingement if the metal rim of the cup does not overlap the ceramic edge of the liner [63]. The studies demonstrated traces of regular impact along the medial rim in the acetabular components removed. An impact at the moment of movement could shift the head from the center to the rim, which increased the pressure between the friction pair, shifting the contact patch and the force vector [8, 28]. In this case, the thin liquid film was destroyed leading to the effect of dry friction.

The hallmark of the rim loading is the presence of wear bands in components [32]. The distance from the contact patch to the rim of the liner (CPR) is essential since a direct correlation is reported between the presence of noise and a decrease in CPR [32]. Other studies indicate that impingement may have occurred in patients only when rising from a chair or climbing stairs. The pressure in the friction surface increases significantly with such movements, when an individual is on one supporting limb [64]. The wear rate does not increase even in malalignment [65]. This situation is a predictor of the risk of noise and explosive destruction of ceramics. Walter W.L. et al. explored 12 ceramic components removed during revision in patients with noise complaints, and all components showed signs of the rim wear. The wear thickness was 94 μm, compared to 72 μm in patients without noise. This difference was not significant. However, Walter W.L. et al. reported the liner tending to tilt out of the acetabular shell opposite the applied load with separation of the surfaces measuring 40 μm in the experiment. This separation could allow the acetabular shell to emit a squeaking sound [6]. The study demonstrated that the load on the anterior rim of the liner could be associated with excessive anteversion and inclination of the acetabular component with the load on the posterior rim of the liner being reduced [64]. This mechanism is considered one of the reasons for the dissociated liner and the acetabular component [66]. Posterosuperior marginal load occurs 4 times greater than anterosuperior load [23].

Recent studies have reported the functional orientation of the acetabular component, and it was found that the components required individual selection of anteversion and inclination angles when using a ceramic friction pair in accordance with the philosophy of kinematic arthroplasty [67, 68].

Film damage. The destruction of the synovial film in a tribological pair can be affected by excess pressure in the contact patch, that can occur with high BMI and inadequate placement correct of the components [69]. Insufficient substance to reduce surface friction with use of large diameters can increase the risk of vibration and cause noise [70]. A liquid film acting as a lubricant requires a fine balance of a number of factors, which include sliding speed (1), viscosity of the lubricating fluid (2), surface roughness (3), gap (4), contact pressure – patch (5) [71]. Impaired lubrication by a liquid film can occur as a result of rim loading (reduction of contact area) and the appearance of third bodies (ceramic fragments) in the tribological couple [49].

Third body. Wear streaks were observed in the ceramic components removed from patients with noise complaints. Toni A. et al. reported a high level of ceramic particles found in the aspirates of the artificial joint in patients with complaints of noise. This may indicate the presence of a third body [49, 72]. Lucchini S et al. hypothesized a multi-stage crack growth mechanism to occur following damage at the head-neck taper interface [12].

Microseparation is another theory for the appearance of wear bands [45]. The use of large heads has become popular in recent years. However, this may be the cause of microseparation between the head and the cup due to a small opening angle, which can lead to constant microcollisions in the pair and cause noise [73].

Resonance. The rotational force exceeds the static force in the friction pair at the movement, which leads to the acceleration of one articular surface relative to the other. This causes vibration of ceramic components [6]. Recent studies have shown that the acetabular and femoral components play the role of vibration oscillator [6]. Resonance does not occur if the frequency of vibration does not match the frequency of the component. Fan N. et al. reported the noise frequency of ceramics of 400-7500 Hz [6, 58]. Modal analysis was performed to understand the resonance of the components, which showed that the ceramic liner and cup alone could not resonate, but the ceramic head with the femoral component showed resonance in several modes and planes [6]. The metal composition and design of the implant can influence noise. And this indicates that the vibration frequency of endoprosthetic components is at the same level with noise in this range [62]. Metal components are vibration amplifiers [74].

Features of noise

Noise is described as knocking, clicking, grinding, creaking. The audible sounds are interpreted as creaking which is the most common of the noises described [22, 27]. The authors reported a revision rate of 0.2 % due to squeaking [19]. Creaking has been described as a high-frequency and highly audible sound that is unique to ceramics [28]. It is often painless but affects quality of life. Moreover, noises can be indicators of inadequate placement of endoprosthetic components [28]. Noise in friction pairs was first described in 2008 [73]. Glaser D. et al. were the first to describe characteristics of noise and the classification.

Knocking (*clicking*) is defined as a sign of stress, representing temporary impulses of short duration and high amplitude (like a high-pitched note) [73]. This sound can be identified in patients when the head is separated from the socket, which can occur in the presence of a slot [73]. Schroder D. et al. reported a clicking noise as the most common noise instead of a creaking noise [75]. A similar observation was reported in other studies [17, 33].

Grinding is defined as a high-frequency audible sound resulting from forced vibration generated by a driving force, resulting in a dynamic response [6]. It is observed with intense, sliding movement between the head and the acetabulum in full contact [73]. Shah M.S. et al. reported squeaking as the most common type of noise, accounting for half of the noise (7.7 out of 14.7 %) [22].

Crunching indicates cracking of ceramic components [49]. The mechanism consists in the formation of a small and hard abrasive that also rubs between the ceramic components. This indicates the appearance of abrasive noise, which can be compared to the sound of sand rubbing against glass. This noise must be identified urgently to prevent the spread of particles into the surrounding soft tissue resulting from the patient's motor activity [76].

The nature of noise can be classified into two types. The authors of a recent experimental study on the occurrence of noise in three different conditions (dry friction, water and blood plasma) found that high-frequency noise occurred only with dry friction with a standard tilt of the acetabular component according to ISO 14242-1 which indicated the adhesive noise. Audible sounds appeared everywhere with the same specified conditions with a change in the edge slope corresponding to ISO 14242-4.

Dry test conditions are inappropriate when assessing ceramic squeaking, as noise will be generated at any angle. It has been demonstrated that noise occurs when edge pressure is applied to the liner with any lubrication condition [77]. It can be assumed that the integrity of the lubricating film is disrupted with edge pressure, movement and impact leading to dry contact and generating noise. Squeaking may indicate an impaired liquid film due to a high coefficient of friction [71]. Another experimental study aimed to detect component wear using acoustic emission showed differences in the sounds of adhesive and abrasive wear [78]. Adhesive wear can be considered dry friction in the case of a ceramic friction pair, and abrasive wear can be considered in the presence of a third body. Both experiments demonstrated the noise being high-frequency and instantaneous with the film being intact and the frequencies decreased and their duration increased with dry friction or with the integrity of the surface being impaired. The noise frequency mainly fluctuated in the range perceived by humans [79, 80].

An analysis of the literature to interpret the types of noise in a ceramic friction pair reflected questions to which the answers are ambiguous, since there is no single consensus on the classification and type of noise [25]. There are a large number of laboratory studies on friction pairs for wear resistance and noise production exploring the noise phenomenon [81]. However, not all the models can reproduce a human joint. First, the tribological couple must have good wettability for the suction effect and have a lubricating fluid like synovial fluid. Secondly, we must understand that noise is mainly produced in the friction pair of the endoprosthesis at a high pressure and can be obtained with statics of the lower limb and dynamics of the pelvis. The acetabular component must move relative to the axis of the femoral head of the hip endoprosthesis and not otherwise.

Clinical management of patients with hip noise

Patients undergoing THA with a ceramic friction pair should be aware of the risks of noise in the joint and should contact the operating surgeon if noise occurs. The femoral component must be carefully selected to prevent noise considering spinopelvic relationship according to the principle of kinematic arthroplasty [81]. Navigation is practical for implanting endoprostheses with a ceramic friction pair that can reduce the risk of ceramic splitting by 2.7 times and promote optimal spatial orientation of the endoprosthetic components [22]. When a patient complains of noise in the joint the orthopaedic surgeon must rule out a fracture of ceramic components using computed tomography [6]. The majority of patients with fractured ceramic components have no history of trauma, and the events leading to the noise are trivial [14, 48, 82, 83]. Noise with a ceramic friction pair can become a predictor of the risk of endoprosthetic destruction [83]. A recent study demonstrated that fracture of ceramic components is rather to continuous exposure to certain forces than as a result of one-time trauma [12]. Levêque R. et al. reported no delayed ceramic implant breakage in THA at a median 3 years follow-up [84]. CT is used to measure the position and spatial orientation of components. Having ruled out splitting, the specialist must determine whether the noise is acceptable or unacceptable. Acceptable noise is typically the result of posterior edge loading and probably occur with edge loading when the hip is flexed, such as with rising from a chair or with climbing a high step [64]. This type of noise is usually associated with some kind of excessive movement, which can be avoided by using an orthotic regimen and limiting the provoking movements. Disenabling noise occurs during a normal movement cycle and can be accompanied by pain and disturbs the patient [64]. This type of noise is believed to be associated with loading on the anterior edge of the liner. Walter W.L. et al. recommended revision surgery for noises that are accompanied by pain, or for incorrect orientation of components [6]. If the noise affects the patient's lifestyle and if there are indications the specialist should perform revision surgery. Examination of synovial fluid aspirate can be an addition to diagnosis [72]. The presence of particles of 2-5 microns in the aspirate may indicate an early stage of fractured ceramic components. Fragments exceeding 5 μm indicate macroscopic destruction in ceramics [49].

Traina F. et al. reported 81 % of cases with the noise being associated with the fracture of the ceramic friction pair in patients with audible noise at the site of the prosthetic joint based on the synovial fluid analysis. In the group of patients, only there were Signs of ceramic destruction were seen in 6.1 % of cases with a silent course of the noise, which makes us treat ceramic friction pairs with some caution [85]. Moreover, it has been repeatedly reported that a fractured ceramic component was detected in patients who previously had noise complaints [31]. Stripe wear and metal transfer to ceramic components were reported in 100 % of cases of noise [31, 35]. Inagaki K. et al. described a 2-stage prospective screening of patients with a ceramic friction pair with the number of patients with complaints increasing with each screening, and patients who had noise complaints in previous screenings had them in subsequent screenings demonstrating an accumulation effect of patients with noise complaints [25]. One patient who complained of squeaking was subsequently revised for a fractured ceramic liner.

Kim M.W. et al. reported changes in the frequency and pitch of noise in patients in a multi-stage control observation [86]. Due to the versatility of noise in a ceramic friction pair, it is not entirely clear whether noise production is the cause of ceramic splitting or microdestruction in a ceramic friction pair with subsequent complete separation of the component. The splitting of the ceramic components of a friction pair results in repeated revisions despite its statistical insignificance. The Australian registry demonstrated that the rate of second revision of 29.6 % over 3.5 years after fracture of ceramic components [11].

A ceramic pair is recommended for young and active patients due to high survival rates and excellent laboratory results for wear [87]. However, the ceramics paradigm needs to change due to recent research. Use of ceramics for a young patient suggests a lifetime choice of a ceramic friction pair. Subsequent revisions can be associated with a friction pair other than a ceramic one. A "ceramics-polyethylene" friction pair can be a method of choice for young and active patients with a "ceramics-ceramics" pair offered for a subsequent revision. Fang Y. et al. reported an insignificant difference in the wear of friction pairs and an insignificant statistical difference in complications in a meta-analysis of comparative randomized controlled studies of ceramic-ceramic and ceramic-polyethylene friction pairs [88]. Jack C.M. et al. reported the results of revisions at 8.3 years with a metal or ceramic head with a polyethylene liner being replaced with a ceramic-ceramic friction pair. Patients reported no noise at the site of the prosthesis [89].

CONCLUSION

Literature review on the problem of ceramic friction pairs demonstrated a lot of unresolved issues regarding functioning of ceramic friction pairs in THA, which force us to be cautious about the choice of the ceramic pair. The use of ceramic pairs suggest measures to be taken to ensure optimal functioning of the pair through ideal implantation of prosthetic components using robotic technologies and subsequent medical examination of patients. The assessment of noise in a functioning endoprosthesis is considered an unreliable and very expensive method with the size of the components and the design causing different sound frequencies. Patient related factors can affect the frequency of the sound with the amplitude, duration and nature of the sound to be assessed [6, 73]. The accumulated database can help formulate a new hypothesis for the genesis of noise, methods for their correction and prediction of splitting ceramics. The ceramic friction pair is not as good as it is advertised, which, admittedly, is a good job of marketers, despite the fact that the ceramic friction pair can play the role of an "iceberg" for any Titanic.

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Information about authors:

1. Baikozho R. Tashtanov – resident, b.tashtanov95@gmail.com, https://orcid.org/0000-0002-8553-9712;
2. Irina A. Kirilova – Doctor of Medical Sciences, Deputy Director for Research, Associate Professor, irinakirilova71@mail.ru, https://orcid.org/0000-0003-1911-9741;
3. Daria V. Pavlova – dariiysss@yandex.ru, https://orcid.org/0009-0005-0051-2481;
4. Vitaly V. Pavlov – Doctor of Medical Sciences, Head of Department, Professor, pavlovdoc@mail.ru, https://orcid.org/0000-0002-8997-7330.

Contribution of the authors:

1. Tashtanov B.R. – conceptualization, formal analysis, data processing, writing – initial version, visualization.
2. Kirilova I.A. – control, writing – reviewing and editing.
3. Pavlova D.V. – formal analysis, data processing, writing – reviewing and editing.
4. Pavlov V.V. – conceptualization, methodology, validation, visualization, project management.