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Trends of ‘Artificial Intelligence, Machine Learning, Virtual Reality and Radiomics in Urolithiasis’ over the last 30 years (1994–2023) as published in the literature (PubMed): a Comprehensive review.

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ABSTRACT

Purpose: To analyze the bibliometric publication trend on the application of “Artificial Intelligence (AI) and its subsets (Machine Learning–ML, Virtual reality–VR, Radiomics) in Urolithiasis” over 3 decades. We looked at the publication trends associated with AI and stone disease, including both clinical and surgical applications, and training in endourology.

Methods: Though a MeshTerms research on PubMed, we performed a comprehensive review from 1994–2023 for all published papers on “AI, ML, VR and Radiomics”. Papers were then divided in three categories: A-Clinical (Non-surgical), B-Clinical (Surgical) and C-Training papers, and articles were then assigned to 3 periods: Period-1(1994–2003), Period-2(2004–2013), Period- 3(2014–2023).

Results: 343 papers were noted (Groups A-129, B-163 and C-51), and trends increased from Period-1 to Period-2 at 123%($p=0.009$), and to period-3 at 453%($p=0.003$). This increase from Period-2 to Period-3 for groups A, B and C was 476%($p=0.019$), 616%($p=0.001$) and 185%($p<0.001$) respectively.

Group A papers included rise in papers on “stone characteristics”(2100%; $p=0.011$), “renal function”(0.002), “stone diagnosis”(192%), “prediction of stone passage”(400%) and “quality of life”(1000%).

Group B papers included rise in papers on “URS”(2650%, $p=0.008$), “PCNL”(600%, $p=0.001$) and “SWL”(650%, $p=0.018$). Papers on “Targeting”(453%, $p<0.001$), “Outcomes”(850%, $p=0.013$) and “Technological Innovation” ($p=0.0311$) had rising trends.

Group C papers included rise in papers on “PCNL”(300%, $p=0.039$), and “URS”(188%, $p=0.003$).

Conclusion: Publications on AI and its subset areas for urolithiasis have seen an exponential increase over the last decade, with an increase in surgical and non-surgical clinical areas as well as in training. Future AI related growth in the field of endourology and urolithiasis is likely to improve training, patient centered decision making and clinical outcomes.

MAIN TEXT

1. Introduction

In the past decades, urologists have shown an increasing interest in how technological improvements could play a role in daily practice, with clinical interest and financial investments following this trend. Two major subjects have seen growing research of technological application in urolithiasis: 1- Computed driven analysis of clinical features to diagnose stones, create patient centered models and predict treatment outcomes; 2- Simulation-based device that can help urologists overcome difficult anatomical situations as well as helping in simulation training ¹.

Artificial intelligence (AI) has proven itself as a reliable system to help physicians in diagnosis, decision-making process and treatment. In healthcare, AI refers to all algorithms, devices and applications based on computer system and big data ². Its application in the field of endourology are numerous, from early diagnosis and personalized treatment to prediction of outcomes and complications. The most common example of this is how AI can easily and precisely identify stone dimension and composition from ultrasound (US) and computed tomography (CT) images. Moreover, it has also been proposed to predict spontaneous stone passage and outcomes of endourological procedures ³. Machine learning (ML) is a subtype of AI that is used in urolithiasis for both diagnosis and treatment planning ⁴, relying on computer analysis for decision-making process, as well as other techniques including deep learning (DL), artificial neural networks (ANN) and natural language processing (NLP) ⁵.

ANN, DL and ML have already been incorporated in radiomics-driven learning models that surpass the human ability to detect images and hidden data. Radiomics is in fact a quantitative method that improves precision medicine by extracting extensive data from radiographic images and analyzing them through AI software. Radiomics has been recently used in urolithiasis to predict pre-operative stone free rate (SFR) for shockwave lithotripsy (SWL) and also post-procedural complications, and it shows a great potential in optimizing disease management ⁶.

Alongside these computational systems, another field of technological research is making its great impact in endourology simulation training: virtual reality (VR), augmented reality (AR) and mixed reality (MR) are systems that can be equipped with medical tools to simulate endourological intervention in a realistic setting, such as ureteroscopy (URS) and percutaneous nephrolithotomy (PCNL). The potential advantage of artificial intelligence in PCNL is related to remote access, reduced number of needle punctures, and less radiation exposure during renal access. Residents, students but also trained urologists can benefit with these devices to improve their skills or even simulate patient-specific anatomical features and plan a personalized intervention ⁷. For simulation-based training, urology residents have found three-dimensional (3D) printed models another useful tool that can help them gain the surgical skills required in endourology. 3D-printing is a relatively new technology and has only partially been applied in urolithiasis. Since the first 3D-printed models in the 80s, surgeons started using these models for preoperative planning and practice only in the XXI century, with a rapid expansion when customized medical devices became a focus. Though, it has enormous potential in building patient-specific models for surgical planning, patient counselling, and training residents to perform high-risk procedures such as PCNL, overcoming their initial experience barrier ⁸.

Technological innovations and improvements in management of urolithiasis are ever increasing, hand in hand with urologists' attention for devices that can help them through the diagnostic and therapeutic processes ⁹. An increasing number of publications reflects this interest over the last decades, while a formal evaluation of such a bibliographic trend has remained under-reported. For this purpose, we conducted this study looking at the publication trends associated with the application of AI, ML, VR, 3D printing and radiomics in urolithiasis.

2. Materials and methods

A review of the literature was conducted using MeSH terms, title words, and key words in PubMed over the last 30 years, from January 1994 to February 2023 for all published papers on "Urolithiasis".

2.1 Search strategy and study selection

This study was performed according to Cochrane methodology. A search protocol was developed by the author team. All relevant abstracts regarding specific topics were identified through search on online database PubMed year by year from 1994 to 2023. Keywords used for searching included: “Urolithiasis”, “Kidney calculi” and “Stones”. MESH terms used in this screening process were: “Artificial Intelligence”, “Machine Learning”, “Deep Learning”, “Artificial Neural Network”, “natural Language Processing”, “Radiomic”, “Virtual Reality”, “Augmented Reality” “Mixed Reality”, “URS Simulation”, “PCNL Simulation”, “3D Model”, “Robotic URS”, “Flexible ureteroscopy”, “PCNL Automated Targeting” and “PCNL Needle Targeting” (Fig 1). No language restrictions were applied, and all English and Non-English full-length articles with abstracts were included in the study. Reviews, case reports and case series were all included. Studies without a published abstract and animal studies were excluded.

2.2 Evidence acquisition: criteria for including studies for this review

Inclusion criteria:

- All full-length English language studies
- All non-English studies with abstracts written in the English language
- Studies reporting on artificial intelligence, machine learning, virtual reality and radiomics in urolithiasis:
 - Diagnosis, stone characteristic, clinical management
 - Treatment and interventions—open surgery, laparoscopic surgery, pyelolithotomy, shockwave lithotripsy (SWL), PCNL, and URS.
 - Training and simulation in urolithiasis intervention.

Exclusion criteria:

- Studies for non-urolithiasis conditions
- Animal studies

Two authors (C.N., C.C.) independently performed a literature search to identify studies and discrepancies were resolved after input and discussion with the senior author (BKS).

Extracted articles were then divided in three subgroups according to field of interest: 1- Clinical (Non-Surgical) or Clinical setting, 2- Clinical (Surgical) or Surgical procedures, and 3- Training (Fig 2). Each subgroup was then divided into three 10-year time periods to compare and identify the contrast of different decades: period-1 (1994-2003), period-2 (2004-2013) and period-3 (2014-2023).

Statistical analysis of the extracted data was performed through the independent *t* test, with a significant threshold level at $p < 0.05$, ruling out possible difference in the data collected from period-1 vs period-2 and period-2 vs period-3.

3. Results

3.1 Overall number of papers on AI in urolithiasis

Over the past three decades, 343 articles have been published on application of AI, ML, DL, VR and radiomics in urolithiasis (non-surgical, $n=129$; surgical, $n=163$; training, $n=51$) (Fig.3). 319 English papers were found and of 24 Non-English articles with English abstracts, 6 were written in Chinese, 9 in Russian, 3 in French, 3 in German and 1 each in Italian, Polish and Spanish (Tab.1).

For non-surgical management, articles included renal function and anatomical features ($n=6$), stone diagnosis ($n=63$), stone volume ($n=9$), stone composition ($n=24$), prediction of risk of infection ($n=9$), treatment planning ($n=10$), prediction of spontaneous passage ($n=7$) and impact on quality of life ($n=1$).

Surgical management articles were analyzed for both procedure and type of surgical application. Surgical procedures included URS ($n=61$), PCNL ($n=107$), SWL ($n=56$), ureteral stent insertion ($n=2$) and pyelolithotomy ($n=2$). Surgical application articles included: technological improvements ($n=8$), improving surgical outcomes ($n=67$) and targeting/surgical planning ($n=88$). For training in endourology, articles included URS simulation ($n=31$), PCNL simulation ($n=30$) and diagnostic training ($n=1$).

Overall number of articles written in period-2 was significantly higher than in period-1, with an increase of 123% ($p=0.009$), but this trend appears even steeper in the last decade, with a notable increase from period-2 to period-3 of 453% ($p=0.003$). Furthermore, a significant rise in number of papers was found in each subgroup from period-2 to period-3 (Fig.4): clinical non-surgical articles increased by 476% ($p=0.019$), surgical papers by 616%

($p=0.001$), and training papers by 185% ($p<0.001$). A summary of statistical results comparing period-2 vs period-3 papers is presented in Tab.5.

A further analysis investigated short-term changes in the last decade. The number of papers published in 2014-2016 were compared with that in 2017-2019 and, in turn, the latter was compared with 2020-2022. An overall increase by 155% in the first 3-year time and by 114% in the most recent period. The positive increase was reflected by all the sub-analysis (clinical non-surgical articles increased by 174%, surgical papers by 103%, and training papers by 38%). Statistical analysis retrieved a significant change in the number of publications for overall number of publications and number of papers with a surgical setting ($p=0.006$ and $p=0.007$ respectively).

3.2 Clinical (non-surgical) papers

From 1996, a total of 129 papers have been published on applications of AI in urolithiasis (Tab.2). Comparing periods, there were 14 papers in period-1 and 17 papers in period-2, while period-3 had more than five-time as many papers, with 98 published papers. A significant rise in publication was noted from period-2 to period-3 (+476%; $p=0.019$).

The increase from periods 2 and 3 was significant for “stone characteristics” ($p=0.011$), “stone volume” ($p=0.010$), “stone composition” ($p=0.040$) and “renal function” ($p=0.002$). “Stone diagnosis” with the use of AI retrieved 63 papers (12 period-1, 13 period-2 and 38 period-3, $p=0.123$). “Risk of infection” ($p=0.166$), “treatment planning” ($p=0.137$), “prediction of stone passage” ($p=0.232$) and “quality of life (QoL)” ($p=0.331$) all rose in number of publications, although it was not statistically significant. Fig.5 shows the different trend of publication on each topic in the different periods.

During the last decade, 38 of 98 articles (38.8%) have been published on “stone diagnosis” and 31 (31.6%) on “stone characteristics”, accounting for more than 70% of the total number of publications.

3.3 Surgical papers

163 papers have been published in the last 30 years on the role of AI in the surgical management of urolithiasis (Tab.3). Of these, periods 1, 2 and 3 had 7, 19 and 137 articles respectively, and there was a rise of 621% ($p=0.001$) between periods 2 and 3.

As shown in Fig.6, overall, “PCNL” dominated with periods 1, 2 and 3 having 3, 13 and 91 publications respectively. There was a rise of 600% ($p=0.001$) between periods 2 and 3. Regarding “URS”, periods 1, 2 and 3 had 4, 2 and 55 articles respectively, with an increase by 2650% ($p=0.008$) between periods 2 and 3. Similarly, “SWL” in periods 1, 2 and 3 had 5, 6 and 45 papers respectively, and there was a rise of 650% ($p=0.018$) between periods 2 and 3. Papers on the role of AI in “Ureteral Stenting” and “Pyelolithotomy” has only been published in the last decade, with only two papers found in our research on each topic. Over the last decade there has been a steep rise in the papers on “Outcomes” (850%, $p=0.013$), “Targeting” (453%, $p<0.001$) and “Technological Innovation” ($p=0.0311$) with 57, 72 and 8 papers published respectively in period-3 (Fig.7). As a result, the main field of interest in the last 10 years has been represented by studies on automatic targeting in PCNL ($n=46$), which accounts for a third of all papers.

3.4 Training papers

Papers regarding the application of VR and AI in endourology training have been published only from 2002 to 2022 (Tab.4). In this timeline, 51 papers were published with a significant increase from period-2 to period-3 ($p<0.001$). Of these, 50 are about surgical training (“URS”: $n=20$, “PCNL”: $n=19$, both procedures: $n=11$) and one about “Diagnostic Training” in radiology. Fig.8 shows the increasing trend of publication on URS- and PCNL-training over the years.

In the last decade, a rise in publication is pointed out by 23 papers on “URS training” (increase: 188%, $p=0.003$) and 24 on “PCNL training” (increase: 300%, $p=0.039$).

3.5 Technology in AI

An analysis of representation of different AI technology was performed (Tab.6).

During period-1, no paper on ML, Radiomics or Robotic application in urolithiasis was found. 3D-modelling accounted for the most of publications in period-1, with 13 manuscripts found. This number increased by 46% in period-2 with 19 publications ($p=0.0167$) and by 400% in period-3, with 95 papers ($p=0.001$).

8 papers on DL in urolithiasis were published in period-1, 14 in period-2 (increase: 75%, $p=0.2406$) and 35 in period-3 (increase: 150%, $p=0.0093$). Only one paper on AR/VR was

found in period-1, while 14 were identified in period-2 and 42 in period-3, with an increase between both time-lines (increase: 1300%, $p=0.1716$ in period-1 vs -2; increase: 200%, $p=0.039$).

Publications on robotics applications of AI rose by 600% ($p<0.0001$) from period-2 ($n=2$) to period-3 ($n=14$). ML accounted for 56 papers, all published in period-3 ($p=0.0185$). Similarly, 10 radiomics-related publications were found in period-3 ($p=0.0030$).

The remaining 20 papers, all published in period-3, did not discuss a single AI-related technology and were hence not better classified.

Discussion

This is one of the first comprehensive trend studies in the field of AI and its subsets in Urolithiasis, looking at publication trends over the last 30 years (1994–2023). With the development of new technologies and their applications in endourology, the number of papers published on this subject has witnessed a dramatic surge.

From the first introduction in healthcare in 1970, AI applications in the medical field increased progressively, reaching a “boom” of production with the Fourth Technological Revolution. AI technologies have expanded and adapted to transform the healthcare industry by reducing spend, improving patient outcomes, and increasing efficiencies overall. Even if there wasn't a specific “breakthrough” that was widely recognized as a game-changer for urolithiasis, AI has been making strides in medical imaging and diagnostics, which large applications in urolithiasis detection and treatment. In the last decade, bibliographic research shows how the interest in AI, ML and VR has increased exponentially, with more and more studies that validate its application in the management of urolithiasis¹⁰. As can be seen from the global trends of interventions in our analysis, these increasing tendencies were seen in non-surgical and surgical management as well as training applications of AI. These have made a greater footprint on surgical management of stone disease¹¹.

As a reflection of the modern breakthroughs in automated systems such as radiomics and ML, alongside their applications first in medical field and then urology, the interest in publications on the matter has increased in the last decade. ANN and ML have been at the

focus of this research, especially in a clinical setting, with the aim to develop automated systems that could precisely diagnose the presence and make-up of stones, predict risk of sepsis and stone recurrence, and even the probability of spontaneous passage ¹. New technologies have been developed and more are to come, with the goal to refine ML algorithms for automated stone recognition and determination of volume, surface and even chemical composition ¹². All these AI-obtained information would play an important role in both pharmacological and surgical management of patients with stone disease, leading to a more accurate stone-related treatment plan ¹³.

The most recent applications of AI in endourology are aimed at improving patient-specific treatment and at precise automatic stone targeting during surgery ¹⁴. With AI technologies and the precise understanding of a patient's anatomy, surgeons are allowed to plan a patient-specific treatment that adapts to the patient's particularities, thus reducing failure and complication risks. This is indeed one of the main focuses in modern medicine, that includes both clinical and surgical strategies.

Performing the trend analysis, PCNL appeared to be by far the procedure the has attracted the highest number of surgical publications, especially in the last 5 years. The particular interest in the application of AI subsets for PCNL procedure can probably be referred to the introduction of automated systems for renal puncture in PCNL, such as robotic devices or VR simulation systems ¹⁵. As renal puncture has always been the challenging point of PCNL, the tools given by AI represent a game-changer, minimizing the need for multiple attempts alongside the complication risks.

Applications of AI can also be found in a preoperative setting as shown by the number of publications in surgical planning over the last decade. The interest in precise planning ranges from 3D models that can help understand the specific anatomy of one patient, renal puncture, to the application of AI in determining the most appropriate laser setting for a specific stone fragmentation ¹⁶. Initially used for implants and prosthetics, 3D-modelling application expanded in the healthcare industry and hence in the urology field. Since the 2010s, 3D printing allowed for the production of complex shapes and structures that were difficult or impossible to achieve with traditional manufacturing methods. Current

investigations on 3D-models are focused on accurate surgical planning, rapid prototyping and iterative design of medical devices, enabling faster development and innovation ¹⁷.

In addition, 3D models are playing a very important role in endourological training, alongside VR, AR and MR ¹⁸. Simulator training allows trainees to practice on high-fidelity models in a low-stress environment, acquiring the fundamental skills needed for difficult endoscopic procedures such as renal puncture. Different simulators have been proposed for teaching purpose, from bench-models and 3D printing, to the most recent high-fidelity fully-immersive simulators ¹⁹. All these devices have proven themselves to help residents through the most difficult steps of PCNL and URS, thereby improving their skills in a virtual setting. Indeed, the benefits given to both patients and trainees are remarkable.

If the impact of AI in the treatment of urolithiasis is a focus of research, the extent of its adoption may vary worldwide. The economic barrier represents an undeniable limit for the inclusion of AI in medical practice, with high cost associated to the development and maintenance. On the other hand, there is still a lack of awareness and acceptance, both from medical staff and patients, that creates a delay in introduction of AI in daily practice. The increase in global deployment of a resource that can implement health services may still be slowed down as a result ²⁰. Yet, the increasing trend of publications reflects the growing interest of urologists towards the applications of AI in daily practice. If image analysis and diagnosis have been deeply investigated and ML software refined, there are several fields that could still witness important innovations. Further technological developments could help predicting the likelihood of recurrence for patients with history of kidney stones, and creating personalized preventive strategies. AI will probably also obtain larger consensus regarding its application in the surgical settings, with real-time assistance and guidance during the endoscopic treatments. Lastly, remote monitoring with AI-powered wearable devices could increase the possibilities for patient's tracking, while chatbots and virtual assistant could provide information and enhance patient engagement.

The role of AI has been explored in several clinical areas of endourology, including automated kidney stone detection, surgical simulation and training, risk assessment, image

guided navigation and predictive model for outcome prediction ^{4,21-23}. However, the day-to-day adoption of this in the routine clinical practice is still lacking.

Strengths and weakness of bibliometric trend analysis

With this review, we aimed to present a comprehensive report of trends of publication on AI applications in Endourology. To our knowledge, this is the first review to evaluate the increasing trend of publications on this subject in the last 30 years.

In order to perform a true mirror of the publication trend and to make it more inclusive, we included articles both in English and in a Non-English language, as long as they had a published English-written abstract. Our research was limited to the PubMed database, and as a consequence some papers published in non-index journals may have been missed. This limitation to our study is supported by the fact that authors feel confident that bibliographic patterns are accurately captured by use of PubMed alone ^{24,25}. Finally, this review covers different kinds of application of intelligent systems in urolithiasis, ranging from a clinical (non-surgical) and preoperative setting to the procedure itself, and postoperative outcomes and follow-up. Future studies analyzing the citation index or nomograms and use of multiple databases might be useful for a more comprehensive study ²⁶.

Conclusion

Published papers on the role of AI and its subsets in the management of stone disease have risen over the last 30 years, with the largest volume of research published in the last decade. In particular, applications in surgical training and treatment have driven significant attention due to an interest in gaining skills and fluency in operative procedures. While the overall number of clinical studies has risen, the main focus seems to be targeted to surgical management of urolithiasis. It seems that technological innovation is still not at its apex and a steep increase in clinical work and related publications is to be expected in future together with its full introduction into daily clinical practice.

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Amelia Pietropaolo – Manuscript editing

Andrea Benedetto Galosi – Manuscript editing

Daniele Castellani – Manuscript editing

Bhaskar Kumar Somani – Conception, editing and supervision

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Abbreviations:

AI – Artificial Intelligence

ML – Machine Learning

VR – Virtual reality

URS – Ureteroscopy

PCNL – Percutaneous nephrolithotomy

SWL – Shockwave lithotripsy

AR – Augmented reality

MR – Mixed reality

Tables

Tab. 1 Number of publications in different field (clinical, surgical, training) over three time periods (period 1: 1994-2003, period 2: 2004-2013, period 3: 2014-2023).

Period	Total	Clinical	Surgical	Training	English	Non-English
Period1: 1994-2003	22	14	7	1	21	1
Period2: 2004-2013	49	17	19	13	44	5
Period3 : 2014-2023	272	98	137	37	253	18

Tab. 2 Distribution of papers about clinical and pre-operative setting on different subjects: renal features, diagnosis of lithiasis, stone volume and composition, prediction of infection, surgical outcomes, spontaneous passage and quality of life.

Year	Total n° of papers	Renal function	Diagnosis	Stone Volume	Stone Composition	Risk of Infection	Treatment plans	Spontaneous Passage	QoL
1996	1		1						
1997	2		2						
1998	0								
1999	1		1						
2000	3		2					1	
2001	5		3		1				
2002	1		1						
2003	1		1						
2004	2		1		1				
2005	1						1		
2006	4		3					1	
2007	3		3						
2008	1		1						
2009	1		1						
2010	1		1						
2011	2		2						
2012	0								
2013	2		1				1		
2014	3		2	1					
2015	2		1	1					
2016	1	1							
2017	3	1	2						
2018	9	1	2		5			1	
2019	11	1	6	2	2				
2020	12	1	1	3	4		2	1	
2021	22	1	7	1	1	3	5	2	1
2022	29		15	1	7	5	1		
2023	6		1		3	1		1	
tot	129	6	61	9	24	9	10	7	1

Tab. 3 Distribution of papers about surgical management on different subject (ureteroscopy, percutaneous lithotripsy, pyelolithotomy, shock wave lithotripsy and ureteral stent).

Year	Total n° of papers	URS	PCNL	ESWL	Ureteral Stent	Pyelolithotomy
1994	1	1	1	1		
1995	0					
1996	0					
1997	0					
1998	1	1		1		
1999	1	1	1			
2000	1	1	1			
2001	0					
2002	1			1		
2003	2			2		
2004	1			1		
2005	2		2			
2006	3		2	1		
2007	0					
2008	0					
2009	1			1		
2010	3		2	1		
2011	1	1	1	1		
2012	3	1	2			
2013	5		4	1		
2014	5	2	4	1		
2015	4		4			
2016	8	3	6	1		
2017	12	6	9	5		

						22
2018	12	2	5	4		1
2019	14	7	10	6		1
2020	17	6	13	4		
2021	25	10	14	7		
2022	35	18	24	15	2	
2023	5	1	2	2		
total	163	61	107	56	2	2

Tab. 4 Distribution of papers about training in different fields (URS, PCNL, diagnostic exams)

Year	Total n° of papers	URS	PCNL	Diagnosis
2002	1	1		
2003	0			
2004	1	1	1	
2005	1	1		
2006	2	2		
2007	0			
2008	3	1	3	
2009	1	1	1	
2010	0			
2011	1	1		
2012	1		1	
2013	3	1	2	
2014	2		2	
2015	2	1	1	
2016	2	1	1	
2017	6	5	3	
2018	2	1	1	
2019	5	1	3	1
2020	5	2	4	
2021	6	5	2	
2022	7	6	5	
total	51	31	30	1

Tab. 5 Summary of trends analysis over the last two time periods.

	Independent t-test	
	p-value	95% CI
Overall number of papers	0,0027	-36,91 to -9,09
CLINICAL MANAGEMENT	0,0191	-14,17 to -1,43
Renal Function and Anatomy	0,0017	-0,94 to -0,26
Diagnosis	0,1232	-5,52 to 0,72
Stone Volume	0,0104	-1,56 to -0,24
Stone Composition	0,0404	-3,51 to -0,09
Risk of Infection	0,1657	-1,96 to 0,36
Treatment plans	0,1372	-1,88 to 0,28
Predicting Spontaneous Passage	0,2323	-0,81 to 0,21
Quality of Life	0,3306	-0,31 to 0,11
SURGICAL MANAGEMENT	0,0012	-18,7 to -5,50
URS	0,0078	-8,85 to -1,55
PCNL	0,0006	-12,69 to -4,11
ESWL	0,0176	-6,68 to -0,72
Stent	0,3306	-0,62 to 0,22
Pyelolithotomy	0,1510	-0,48 to 0,08
Technological innovation	0,0314	-1,33 to -0,07
Outcomes	0,0134	-8,48 to -1,12
Surgical planning and targeting	0,0003	-9,75 to -3,45
TRAINING	0,0004	-4,47 to -1,53
URS	0,0385	-3,11 to -0,09
PCNL	0,0030	-2,90 to -0,70
Diagnosis	0,3306	-0,31 to 0,11

Tab. 6 Analysis of publication on different AI-technologies among the three time periods.

	3D MODEL	AR/VR	DL	ML	RADIOMICS	ROBOTIC	TOTAL
PERIOD-1	13	1	8	0	0	0	22
Period-2	19	14	14	0	0	2	49
Period-3	95	42	35	56	10	14	272
Total	127	57	57	56	10	16	343
%1-2	46%	1300%	75%	0%	0%	0%	123%
P-VALUE	0,0167	0,0002	0,241	N/A	N/A	<0,0001	
%2-3	400%	200%	150%	N/A	N/A	600%	455%
P-VALUE	0,0001	0,015	0,0093	0,0185	0,0030	<0,0001	

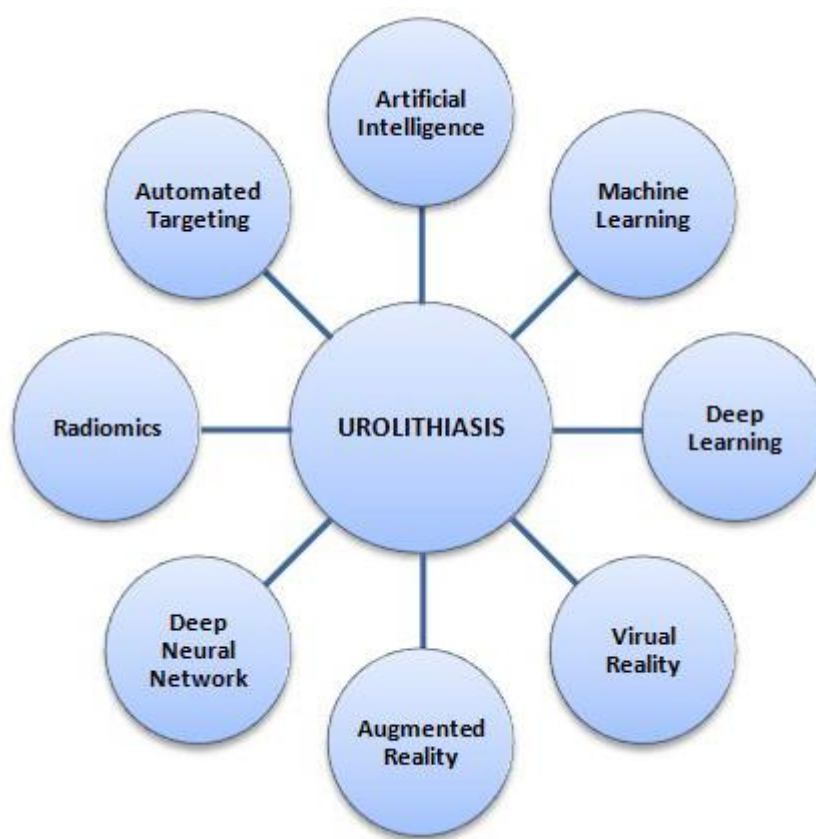


Fig. 1 Mesh terms used in database searching.

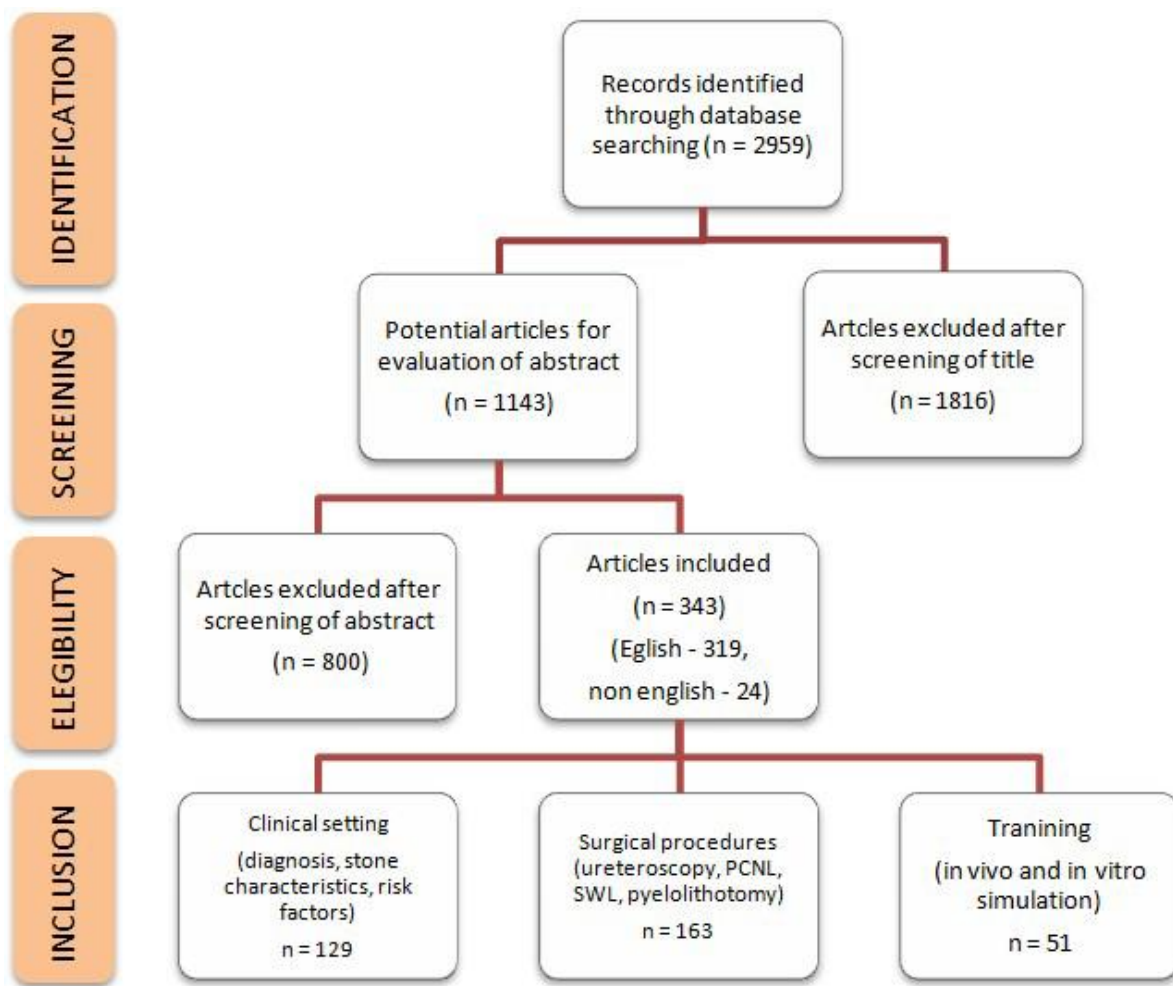


Fig. 2 PRISMA flowchart for identification of the studies

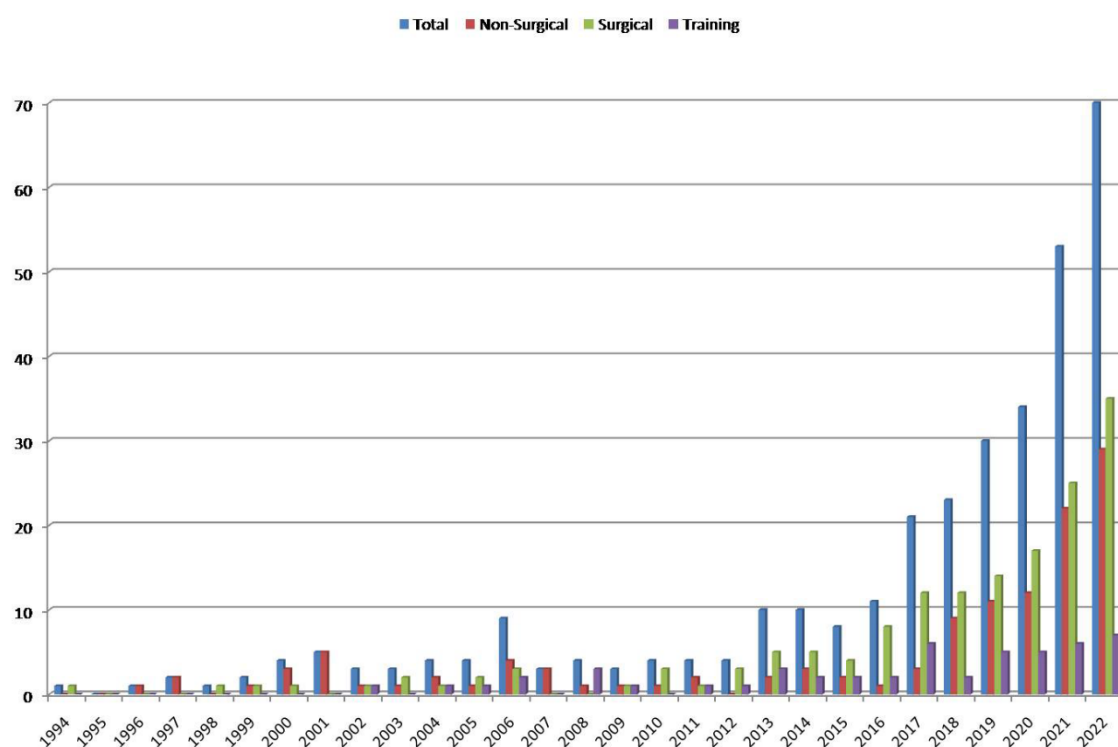


Fig. 3 Trend of publications in different fields (non-surgical, surgical and training settings)

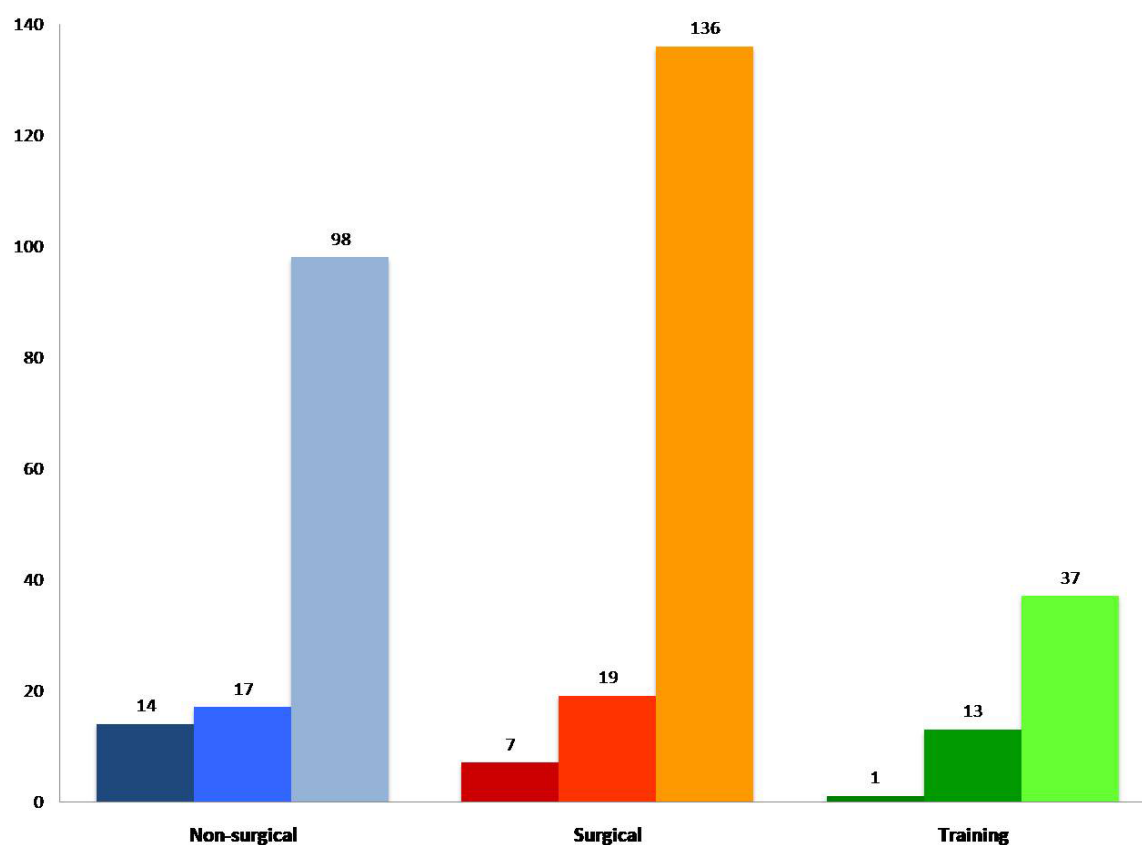


Fig. 4 trend of publications in different field (non-surgical, surgical, training) over three time periods (period 1: 1994-2003, period 2: 2004-2013, period 3: 2014-2023)

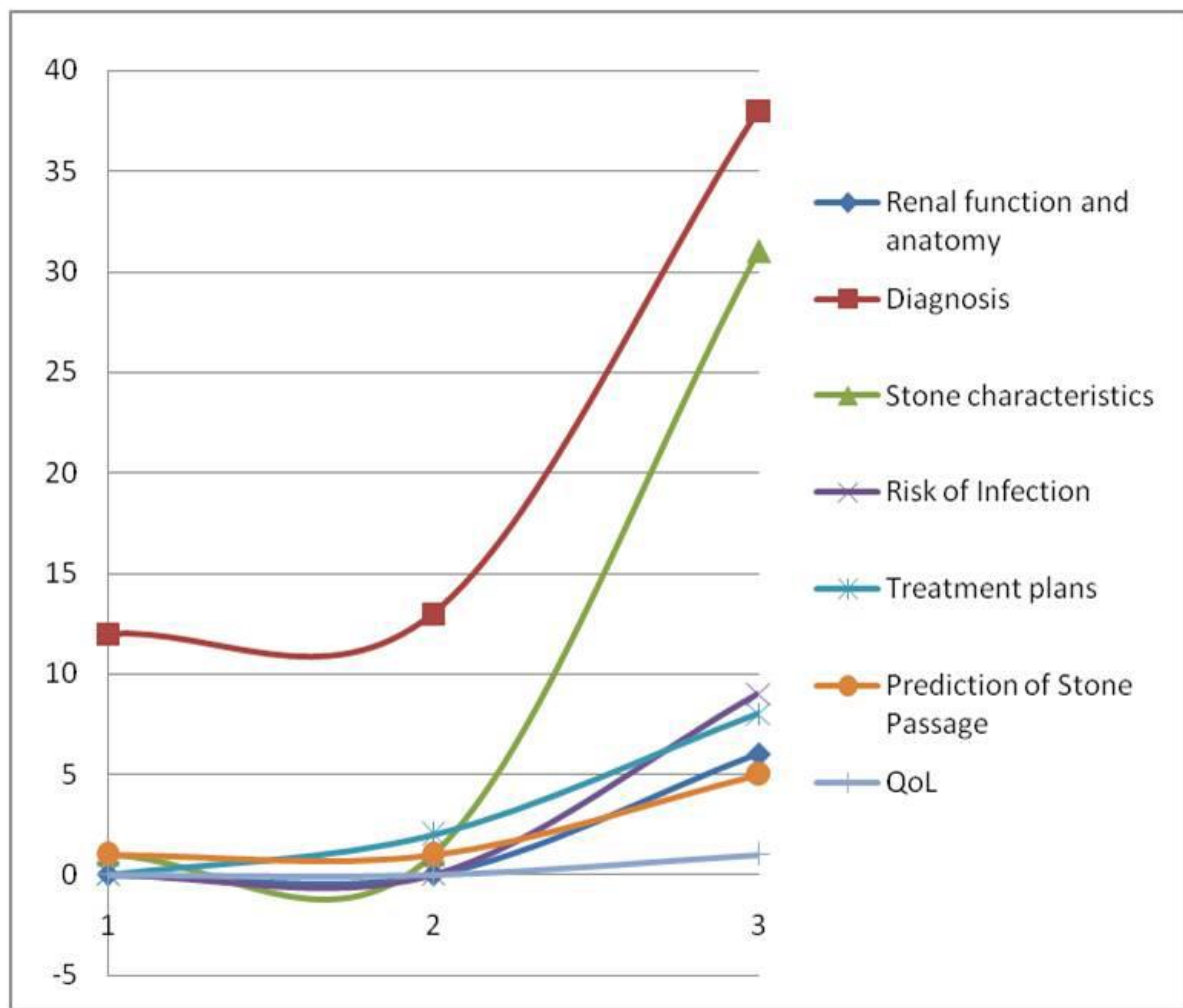


Fig. 5 Increasing trend of publication regarding the use of artificial intelligence and similarities in a clinical urolithiasis setting, divided according to field of interest over the three time periods.

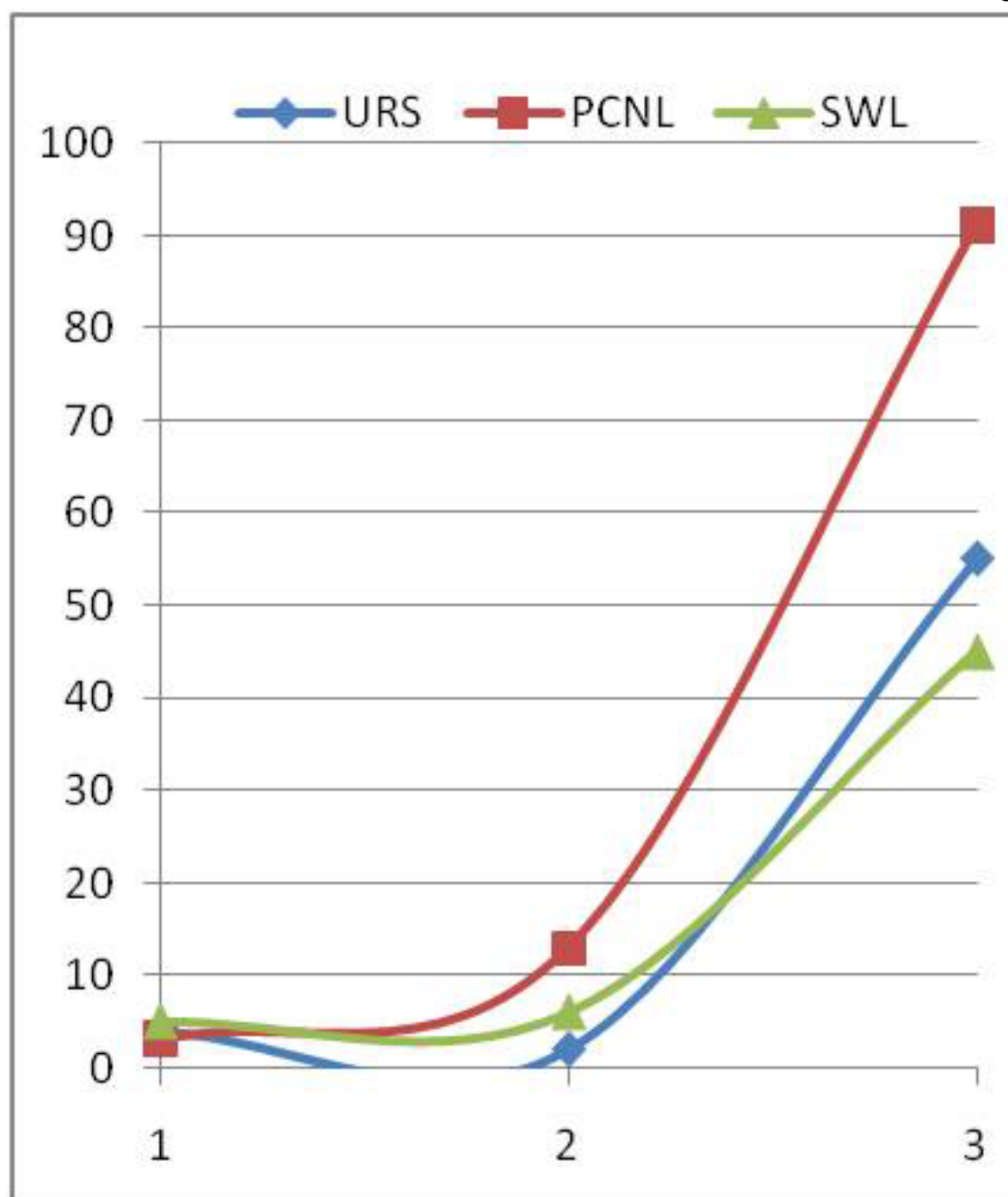


Fig. 6 Trend of publications on surgical management with different surgical techniques (URS, PCNL and ESWL) over the three time periods.

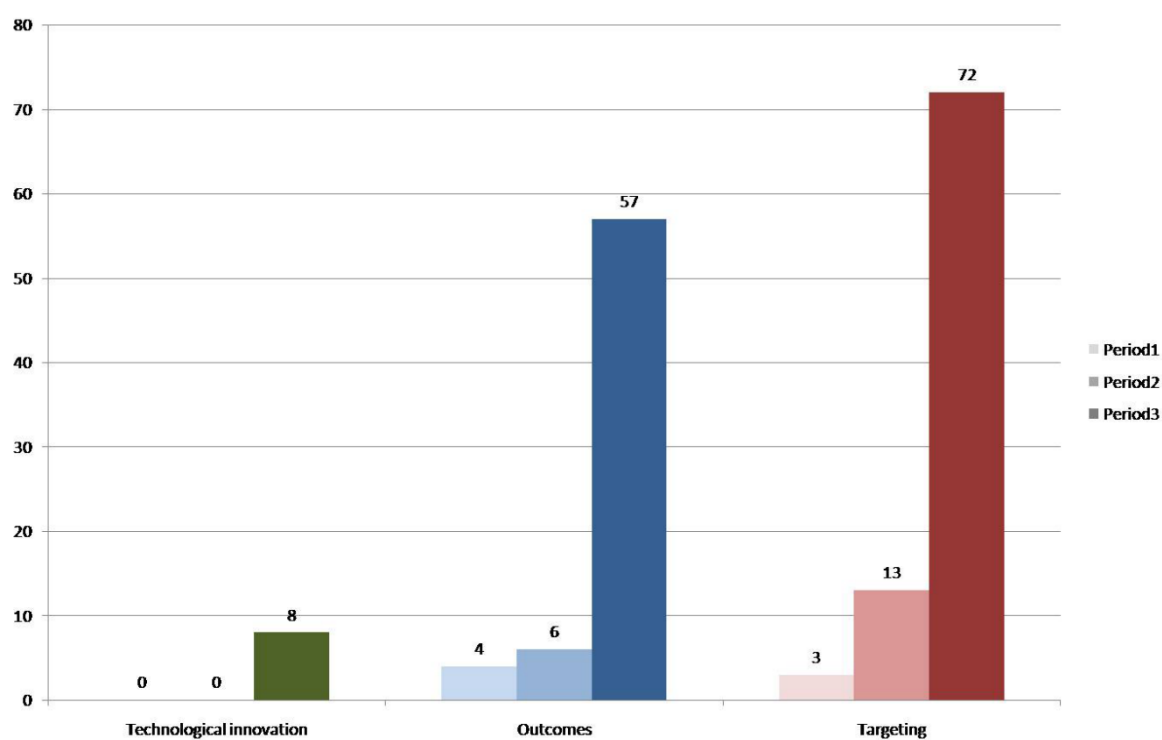


Fig. 7 Trend of publications on surgical management with different focus (technological innovation, surgical outcomes, surgical targeting) over the three time periods.

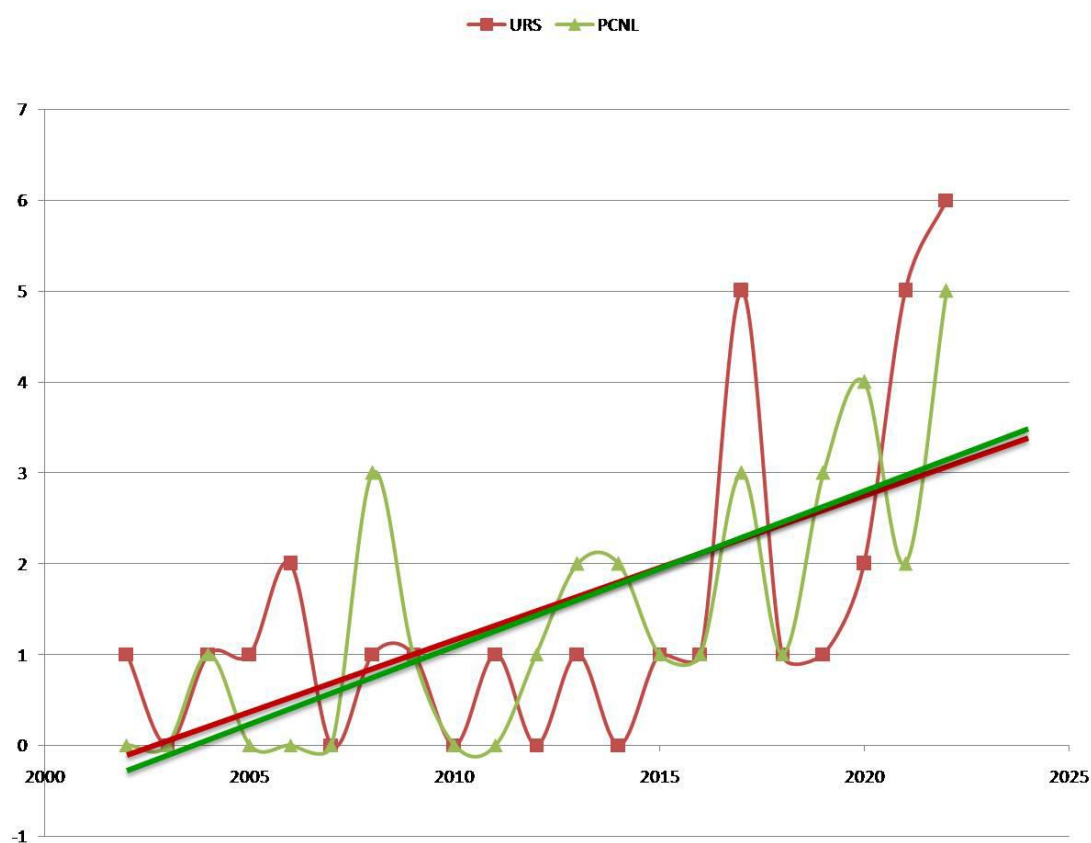


Fig. 8 Trend of publications on training in two different surgical techniques (URS and PCNL) with corresponding linear trend lines.