Systematic Review and Meta-Analysis

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Artificial intelligence with kidney disease

A scoping review with bibliometric analysis, PRISMA-ScR

Sihyung Park, MD[a,*], Bong Soo Park, MD, PhD[a], Yoo Jin Lee, MD[a], Il Hwan Kim, MD, PhD[a], Jin Han Park, MD[a], Junghae Ko, MD, PhD[a], Yang Wook Kim, MD, PhD[a], Kang Min Park, MD[b]

Abstract

Background: Artificial intelligence (AI) has had a significant impact on our lives and plays many roles in various fields. By analyzing the past 30 years of AI trends in the field of nephrology, using a bibliography, we wanted to know the areas of interest and future direction of AI in research related to the kidney.

Methods: Using the Institute for Scientific Information Web of Knowledge database, we searched for articles published from 1990 to 2019 in January 2020 using the keywords AI; deep learning; machine learning; and kidney (or renal). The selected articles were reviewed manually at the points of citation analysis.

Results: From 218 related articles, we selected the top fifty with 1188 citations in total. The most-cited article was cited 84 times and the least-cited one was cited 12 times. These articles were published in 40 journals. *Expert Systems with Applications* (three articles) and *Kidney International* (three articles) were the most cited journals. Forty articles were published in the 2010s, and seven articles were published in the 2000s. The top-fifty most cited articles originated from 17 countries; the USA contributed 16 articles, followed by Turkey with four articles. The main topics in the top fifty consisted of tumors (11), acute kidney injury (10), dialysis-related (5), kidney-transplant related (4), nephrotoxicity (4), glomerular disease (4), chronic kidney disease (3), polycystic kidney disease (2), kidney stone (2), kidney image (2), renal pathology (2), and glomerular filtration rate measure (1).

Conclusions: After 2010, the interest in AI and its achievements increased enormously. To date, AIs have been investigated using data that are relatively easy to access, for example, radiologic images and laboratory results in the fields of tumor and acute kidney injury. In the near future, a deeper and wider range of information, such as genetic and personalized database, will help enrich nephrology fields with AI technology.

Abbreviations: AI = artificial intelligence, AKI = acute kidney injury, ANN = artificial neural network, CAD = computer-aided diagnosis, CKD = chronic kidney disease, GFR = glomerular filtration rate, REVOLVER = repeated evolution in cancer.

Keywords: artificial intelligence, bibliography, kidney, nephrology

1. Introduction

Artificial intelligence (AI) refers to computer algorithms designed to mimic and augment human thought patterns and actions. AIs have been highlighted in the last several years across multiple technical industry fields. Technical terms, such as artificial neural networks (ANNs), convolutional neural networks, deep learning, machine learning, and big data, are now everyday words.

AIs are used in many medical fields owing to the widespread adoption of electronic healthcare records (EHR) and the improvement of big-data storage devices in hospitals. AIs have various applications in healthcare, including drug development, health monitoring, medical-data management, disease diagnosis, and personalized treatment.[1] DXplain, Germwatcher, Babylon, and International Business Machines Corporation's Watson Health are examples of AIs in medical fields.[1] These AI technologies enable medical practitioners to perform their jobs more conveniently and efficiently. Indeed, the possibilities for AI in medical fields are endless. In nephrology, there have been many attempts to predict the prognosis of various types of renal disease with machine learning. Studies on anemia control and arteriovenous fistula survival of hemodialysis patients, cardiovascular events, technical failure of peritoneal dialysis patients, and predicting acute kidney injuries (AKIs) were conducted.[2] After the 1990s, the ANN was used for predicting transplanted kidney survival.[3] Clinical research and guidelines are major components of the current medical area with an evidence-based medical paradigm. However, high economic burden is an obstacle to all clinical research. Data-driven medicine is one way to overcome this hurdle.

The status and growth of dominant areas in a particular field can be determined by noting frequently cited articles. Identifying important and reliable AI journals in medical fields will provide

Editor: Leena Mallik.

The authors have no conflicts of interest to disclose.

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

[a] Department of Internal Medicine, [b] Department of Neurology, Inje University Haeundae Paik Hospital, Busan, Korea.

[*] Correspondence: Sihyung Park, Department of internal medicine, Inje University Haeundae Paik Hospital, 875, Haeundae-ro, Haeundae-gu, Busan 48108, Korea (e-mail: HPN_SHPARK@paik.ac.kr).

How to cite this article: Park S, Park BS, Lee YJ, Kim IH, Park JH, Ko J, Kim YW, Park KM. Artificial intelligence with kidney disease: a scoping review with bibliometric analysis, PRISMA-ScR. Medicine 2021;100:14(e25422).

Received: 18 June 2020 / Received in final form: 17 January 2021 / Accepted: 27 February 2021

http://dx.doi.org/10.1097/MD.0000000000025422

guidelines for cultivating new areas and investigating current positions in depth. The purpose of this bibliometric-analysis study is to find the current position and future direction of AI in the field of nephrology, using the top fifty most-cited articles in terms of data-driven medicine.

2. Methods

Citations regarding AI trends in the fields of nephrology and kidney medicine were analyzed. We examined the frequency and patterns of citations using the bibliometric method, under the banner of the Web of Science (https://www.webofknowledge.com) by Clarivate Analytics. In January 2020, we collected articles published since 1990 with the following words in the title: AI; deep learning; machine learning; and kidney or renal. Next, we selected publications containing renal-specific human data and then selected the top-fifty most-cited articles according to the citation number in sequence. Review articles, editorials, and abstract-only types were excluded. Finally, we manually examined the contents of all the articles.

The characteristics of the analyzed articles were as follows: number of citations, rank, authors, title, year of publication, source titles, and topic categories. As the next step, we divided the listed articles into tertile periods using their publication order (first tertile: 1990–1999, second tertile: 2000–2009, and third tertile: 2010–2019) and reviewed the articles in the same manner. The department, institution, and country of origin were defined by the affiliation of the first author, if there was more than one affiliation.

This study did not need to obtain the approval of an ethics committee or institutional review board due to the study's properties.

3. Results

We found 435 publications with a total of 4194 instances where the keywords were cited. Out of these, 217 were omitted because they did not have human data or kidney- or renal-oriented content (Fig. 1). When the eligible articles were analyzed in publication order by tertile period, eight articles were published before 2000. Fourteen articles were published from 2000 to 2009, and 196 articles were published from 2010 to 2019.

The trends of the topics differed in each tertile. Before 2000, the article topics were as follows: cancer (2), glomerular disease (2), AKIs (2), kidney-transplant related (1), and chronic kidney disease (CKD) (1). In the second tertile (2000–2009), the subjects of the articles were as follows: dialysis-related (5), tumors (2), AKIs (2), the glomerular filtration rate (GFR) measure (1), kidney images (1), kidney stones (1), glomerular disease (1), and transplant-related (1). During the last 10 years (2010–2019), the article topics were as follows: tumors (41), AKIs (30), kidney-transplant-related (30), dialysis-related (20), glomerular disease (17), kidney images (12), CKD (12), kidney stones (10), renal pathology (6), polycystic kidney disease (PKD) (5), drug toxicity (5), the GFR measure (4), and miscellaneous (4) (Fig. 2).

From the 218 publications, we selected the top-fifty most-cited articles and ranked them according to their citation frequency (Table 1). The top-fifty publications had 1,188 citations among them. The article with the most citations had 84 citations and the one with the fewest had 12 citations. The articles were published in 40 journals. The most-frequently cited source titles were from *Expert Systems with Applications* and *Kidney International* (three articles each). Forty articles were published in the 2010s, and seven were published in the 2000s. The top-fifty most-cited articles originated from 17 countries—the USA contributed 16 articles, followed by Turkey, which contributed 4 articles. The

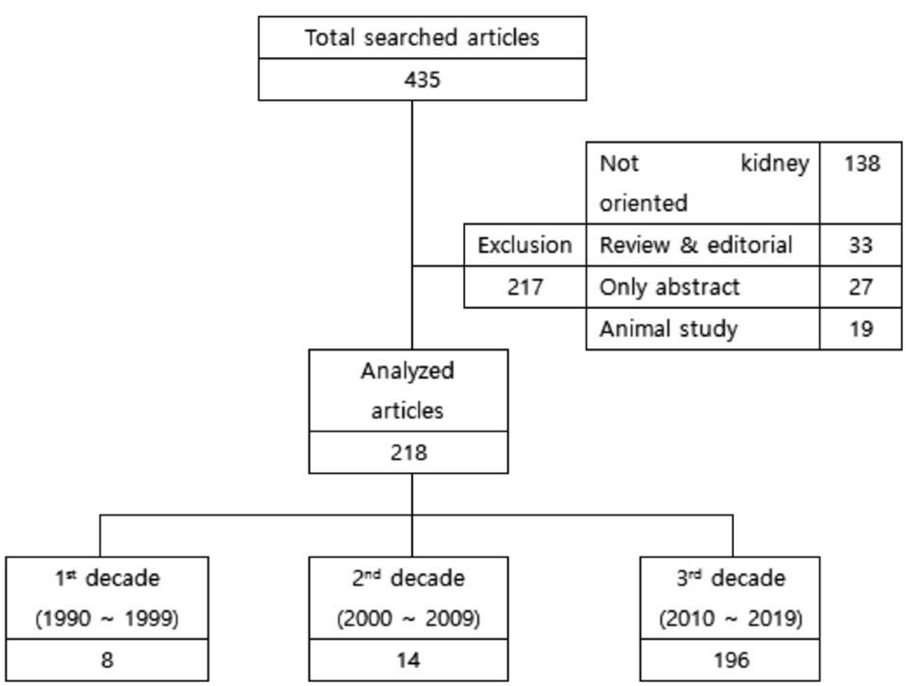

Figure 1. Flowchart of analyzed and excluded articles.

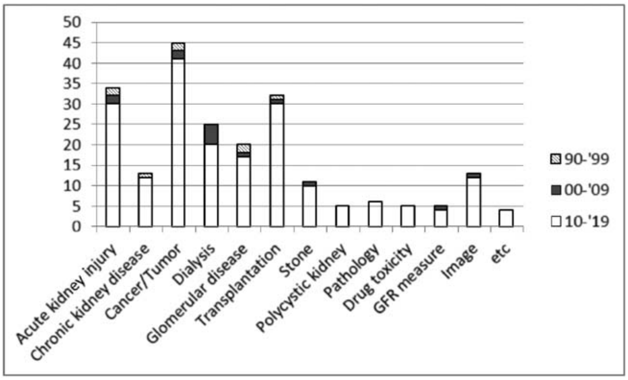

Figure 2. Topics within the top-fifty most-cited articles. From 1990 to 1999, the articles focused on acute kidney injuries, chronic kidney disease, renal cancer, glomerular disease, and transplantation. After 2000, topics regarding dialysis, kidney stones, GFR measures, and kidney images were newly noted. After 2010, topics with polycystic kidney disease, renal pathology, and drug toxicity were newly nominated, and the number of articles about other topics increased.

articles came from five continents: North America (17), Europe (15), Asia (15), Africa (2), and Australia/Oceania (1).

Regarding institutions, the Istanbul Training and Research Hospital in Turkey contributed the most, with three articles (two articles ranked 40th, one article ranked 45th), and the Bioinformatics Institute in Singapore was next, with 2 articles (ranked 16th and 31st). Three authors were co-nominated as the top authors in the top fifty: Burak Kocak from the Istanbul Training and Research Hospital in Turkey (ranked 40th and 45th), Ran Su from the Bioinformatics Institute in Singapore (ranked 16th and 31st), and Rainer Schmidt from the University of Rostock in Germany (ranked 14th and 31st). The main topics of the top fifty articles consisted of tumors (11), AKI (10), dialysis-related (5), kidney-transplant related (4), nephrotoxicity (4), glomerular disease (4), CKD (3), PKD (2), kidney stone (2), kidney image (2), renal pathology (2), and GFR measure (1).

4. Discussion

Feasible practical uses of AI in healthcare settings include medical-image analysis, disease diagnosis, and risk and prognosis prediction, with the purpose of clarifying physicians' decisions, not replacing the physicians themselves.[4,5] The EHR enables more advanced big data. Using these with AI enables physicians to obtain information more efficiently and make more accurate diagnosis and treatment decisions.[6] However, multi-dimensional advanced medical data are related to high computational complexity and low AI-model interoperability. The easiest method of resolving these overfitting problems is to decrease the amount of data, using feature selection and extraction approaches. This dimensionality reduction can make machine learning models simpler and more robust. Most of the articles listed here used this dimensionality reduction to make more precise models.

In the top-fifty articles, AI technologies or algorithms were used to forecast kidney-damage risk, predict future disease status, and identify disease characteristics using image analysis as in Figure 3.

Ten articles were about AKI. AKI is clinically important, with extensive strong evidence for assessing mortality risk.[7] AKI predictions through machine learning models, for example, neural networks and decision trees, are superior to those using conventional regression models. The numerous features and complex relationships of AKI could not be captured with conventional regression. Contrastingly, AIs can easily handle large and complex data automatically. In these 10 articles, the supervised learning AI algorithms, such as support vector machine, decision tree, logistic regression, case-based learning, recurrent neural network, gradient-boosting machine, random forest, and naïve Bayes, were used for AKI. In supervised learning, the algorithm makes a functional map from the variables to the outcomes.[8] One study about biomarker finding used an unsupervised ANN for clustering. The reported prediction accuracies differed among the studies, owing to the study subjects, predictors, validation types, and algorithms. AKI is clinically diagnosed with serum creatinine and urine output, considering the clinical situation.[9] This complexity might cause difficulties in finding the best-matched model. Therefore, AKI has gained significant research interest, owing to the researchers' need to make the best-matched model.

The next topic is CKD. CKD is a major disease in nephrology with a global presence. It is related to anemia, bone disease, heart disease, body–water imbalance, and electrolyte abnormalities. CKD refers to lasting damage to the kidneys that can worsen over time. Thus, early detection and management of CKD are closely related to the patient's quality of life and socioeconomic burden. Three of the top-fifty articles were based on CKD. The topics were nutrition, diagnosis, and progression of CKD. The algorithms used were as follows: multitask temporal as transfer learning, expert systems as supervised learning, and support vector machine as supervised learning with feature selection. When AKI is severe or CKD has progressed to the end stage, renal replacement therapy is required. In an aging society, it is necessary to consider CKD and its complications. Although the subject comprised only 13 articles out of 218 overall, CKD would be a good topic for AI research.

Five articles in the top fifty dealt with dialysis. To determine the dialysis adequacy, algorithms with multilayer perceptrons and iterative dichotomiser 3 as reinforcement learning and ANN as supervised learning were used. For anemia correction and dose-adjusting erythropoietin, a Markov decision process, fitted Q iteration, Q learning, k-means, dose selection, and ANN were used as reinforcement. For kidney transplantation, three articles dealt with graft function and rejection using Bayesian belief networks, support vector machines, linear discriminant analysis, logistic regression, decision trees, and random forest as supervised learning. One article about cardiovascular risk in transplant patients used expert systems and neural networks. Renal replacement therapy, such as dialysis and transplantation, is also a promising topic in terms of anemia correction, dialysis adequacy, phosphate control, graft survival, and many related complications.

Drug toxicity in the kidneys is related to many complications, including AKI and CKD. Four articles in the top fifty dealt with nephrotoxicity. A library for support vector machines,[10] random forest, feature elimination, C5.0 trees, extreme gradient boosting, and k-NN classifiers as supervised learning, was used for model development. In the field of nephrotoxicity, genetic data may be helpful for concise prediction models if possible. Two articles dealt with kidney stones. One was about kidney-stone diagnosis using a fuzzy expert system on various clinical values. The other was about the possibility of a spontaneous kidney-stone passage with an ANN and support vector machine.

Table 1

Top-fifty most-cited articles with titles, first authors, institutions, nationalities, source titles, publication years, and citation numbers.

Rank	Title	1st author	Institute/ Nationality	Source titles	Publi-cation year	No. of citati-ons
1	Pattern analysis of serum proteome distinguishes renal cell carcinoma from other urologic diseases and healthy persons	Yonggwan Won	Chonnam National University Medical School/ South Korea	Proteomics	2003	84
2	Defining cell-type specificity at the transcriptional level in human disease	Wenjun Ju	University of Michigan/ USA	Genome research	2013	83
3	Fast neural network learning algorithms for medical applications	Ahmad Taher Azar	Misr University for Science and Technology/ Egypt	Neural computing and applications	2013	61
4	Application of irregular and unbalanced data to predict diabetic nephropathy using visualization and feature selection methods	Baek Hwan Cho	Hanyang University/ South Korea	Artificial intelligence in medicine	2008	55
5	Prediction of drug-induced nephrotoxicity and injury mechanisms with human induced pluripotent stem cell-derived cells and machine learning methods	Karthikeyan Kandasamy	Institute of Bioengineering and Nanotechnology/ Singapore	Scientific reports	2015	40
6	Texture analysis as a radiomic marker for differentiating renal tumors	HeiShun Yu	Boston Medical Center/ USA	Abdominal radiology	2007	34
7	Application of Machine Learning Techniques to High-Dimensional Clinical Data to Forecast Postoperative Complications	Paul Thottakkara	University of Florida/ USA	Plos One	2016	32
8	Incorporating temporal EHR data in predictive models for risk stratification of renal function deterioration	Anima Singh	Massachusetts Institute of Technology/ USA	Journal Of Biomedical Informatics	2015	31
8	Biomarker discovery with SELDI-TOF MS in human urine associated with early renal injury: Evaluation with computational analytical tools	Kurt J.A. Vanhoutte	Radboud University Nijmegen Medical Centre/ Netherlands	Nephrology dialysis transplantation	2007	31
10	Machine learning-based quantitative texture analysis of CT images of small renal masses: Differentiation of angiomyolipoma without visible fat from renal cell carcinoma	Zhichao Feng	Central South University/ China	European radiology	2018	28
11	The Development of a Machine Learning Inpatient Acute Kidney Injury Prediction Model	Koyner Jay L.	University of Chicago/ USA	Critical care medicine	2018	26
12	Prediction and detection models for acute kidney injury in hospitalized older adults	Rohit J. Kate	University of Wisconsin-Milwaukee/ USA	BMC medical informatics and decision making	2016	26
13	Constructing a nutrition diagnosis expert system	Yuchuan Chen	Taipei Medical University/ Taiwan	Expert Systems With Applications	2012	25
14	The Pattern of Longitudinal Change in Serum Creatinine and 90-Day Mortality After Major Surgery	Dmytro Korenkevych	University of Florida/ USA	Annals Of Surgery	2016	24
14	Medical multiparametric time course prognoses applied to kidney function assessments	Rainer Schmidt	University of Rostock/ Germany	International Journal Of Medical Informatics	1999	24
16	High-throughput imaging-based nephrotoxicity prediction for xenobiotics with diverse chemical structures	Ran Su	Bioinformatics Institute/ Singapore	Archives of toxicology	2016	23
16	Incidence, risk factors and prediction of post-operative acute kidney injury following cardiac surgery for active infective endocarditis: an observational study	Matthieu Legrand	Université Paris Descartes/ France	Critical Care	2013	23
16	Evolving connectionist system versus algebraic formulas for prediction of renal function from serum creatinine	Mark Roger Marshall	Auckland University of Technology/ New Zealand	Kidney International	2005	23
19	Assessing rejection-related disease in kidney transplant biopsies based on archetypal analysis of molecular phenotypes	Jeff Reeve	University of Alberta/ Canada	JCI insight	2017	22
20	Deep Semantic Segmentation of Kidney and Space-Occupying Lesion Area Based on SCNN and ResNet Models Combined with SIFT-Flow Algorithm	Kai-jian Xia	China University of Mining and Technology/ China	Journal Of Medical Systems	2019	21
20	An end stage kidney disease predictor based on an artificial neural networks ensemble	Tommaso Di Noia	Polytechnic University of Bari/ Italy	Expert systems with applications	2013	21
22	Detecting repeated cancer evolution from multiregion tumor sequencing data	Giulio Caravagna	Institute of Cancer Research/ UK	Nature Methods	2018	20
22	Performance of an Artificial Multi-observer Deep Neural Network for Fully Automated Segmentation of Polycystic Kidneys	Timothy L. Kline	Mayo Clinic College of Medicine/ USA	Journal Of Digital Imaging	2017	20
22	Automatic Segmentation of Kidneys using Deep Learning for Total Kidney Volume Quantification in Autosomal Dominant Polycystic Kidney Disease	Kanishka Sharma	IRCCS-Istituto di Ricerche Farmacologiche Mario Negri/ Italy	Scientific Reports	2017	20
25	Bayesian Modeling of Pretransplant Variables Accurately Predicts Kidney Graft Survival	Brown T.S.	Naval Medical Research Center/ USA	American Journal Of Nephrology	2012	19
25	Classification strategies for the grading of renal cell carcinomas, based on nuclear morphometry and densitometry	Christine François	Université Libre de Bruxelles/ Belgium	Journal Of Pathology	1997	18
25	ADMET Evaluation in Drug Discovery. 18. Reliable Prediction of Chemical-Induced Urinary Tract Toxicity by Boosting Machine Learning-Approaches	Tailong Lei	Zhejiang University/ China	Molecular Pharmaceutics	2017	18
28	A medical decision support system for disease diagnosis under uncertainty	Behnam Malmir	Kansas State University/ USA	Expert Systems With Applications	2017	17
28	Diagnosis of Chronic Kidney Disease Based on Support Vector Machine by Feature Selection Methods	Huseyin Polat	Gazi University/ Turkey	Journal of medical systems	2017	17
28	Artificial intelligence: A new approach for prescription and monitoring of hemodialysis therapy	Ahmed I. Akl	Mansoura University/ Egypt	American Journal Of Kidney Diseases	2001	17
31	A clinically applicable approach to continuous prediction of future acute kidney injury	Nenad Tomašev	DeepMind/ UK	Nature	2019	16
31	Quantitative Ultrasound for Measuring Obstructive Severity in Children with Hydronephrosis	Juan J. Cerrolaza	Children's National Health System/ USA	Journal of urology	2016	16
31	Prediction of delayed graft function after kidney transplantation: comparison between logistic regression and machine learning methods	Alexander Decruyenaere	Ghent University Hospital/ Belgium	BMC medical informatics and decision making	2015	16

(*continued*)

Table 1

(continued).

Rank	Title	1st author	Institute/ Nationality	Source titles	Publi-cation year	No. of citati-ons
31	Supervised prediction of drug-induced nephrotoxicity based on interleukin-6 and-8 expression levels	Ran Su	Bioinfromatics Institute/ Singapore	BMC bioinformatics	2014	16
31	A prognostic model for temporal courses that combines temporal abstraction and case-based reasoning	Rainer Schmidt	Universität Rostock/ Germany	International Journal Of Medical Informatics	2005	16
31	Cardiac risk stratification in renal transplantation using a form of artificial intelligence	Thomas F Heston	Oregon Health Sciences University/ USA	American Journal Of Cardiology	1997	16
37	Computer-aided detection of exophytic renal lesions on non-contrast CT images	Jianfei Liu	National Institutes of Health Clinical Center/ USA	Medical Image Analysis	2015	15
37	Optimization of anemia treatment in hemodialysis patients via reinforcement learning	Pablo Escandell-Montero	University of Valencia/ Spain	Artificial intelligence in medicine	2014	15
37	A novel approach for accurate prediction of spontaneous passage of ureteral stones: Support vector machines	F Dal Moro	University of Padova/ Italy	Kidney International	2006	15
40	Decision tree and random forest models for outcome prediction in antibody incompatible kidney transplantation	Torgyn Shaikhina	University of Warwick/ UK	Biomedical Signal Processing And Control	2019	14
40	Radiogenomics in Clear Cell Renal Cell Carcinoma: Machine Learning-Based High-Dimensional Quantitative CT Texture Analysis in Predicting PBRM1 Mutation Status	Burak Kocak	Istanbul Training and Research Hospital/ Turkey	American Journal Of Roentgenology	2019	14
40	Clear Cell Renal Cell Carcinoma: Machine Learning-Based Quantitative Computed Tomography Texture Analysis for Prediction of Fuhrman Nuclear Grade	Ceyda Turan Bektas	Istanbul Training and Research Hospital/ Turkey	European Radiology	2019	14
40	Development of Biomarker Models to Predict Outcomes in Lupus Nephritis	Bethany J. Wolf	Medical University of South Carolina/ USA	Arthritis & Rheumatology	2016	14
40	Ratsnake: A Versatile Image Annotation Tool with Application to Computer-Aided Diagnosis	D.K. Iakovidis	Technological Educational Institute of Lamia/ Greece	Scientific World Journal	2014	14
45	Textural differences between renal cell carcinoma subtypes: Machine learning-based quantitative computed tomography texture analysis with independent external validation	Burak Kocak	Istanbul Training and Research Hospital/ Turkey	European Journal Of Radiology	2018	13
45	An international observational study suggests that artificial intelligence for clinical decision support optimizes anemia management in hemodialysis patients	Carlo Barbieri	Fresenius Medical Care/ Germany	Kidney international	2016	13
45	Efficient Small Blob Detection Based on Local Convexity, Intensity and Shape Information	Min Zhang	Mayo Clinic/ USA	IEEE transactions on medical imaging	2016	13
48	Calibration drift in regression and machine learning models for acute kidney injury	Sharon E Davis	Vanderbilt University School of Medicine/ USA	Journal of the American medical informatics association	2017	12
48	Differentiation of fat-poor angiomyolipoma from clear cell renal cell carcinoma in contrast-enhanced MDCT images using quantitative feature classification	Han Sang Lee	Korea Advanced Institute of Science and Technology/ South Korea	Medical Physics	2017	12
48	Application of rough set classifiers for determining hemodialysis adequacy in ESRD patients	You-Shyang Chen	Hwa Hsia Institute of Technology /Taiwan	Knowledge And Information Systems	2013	12

CT = computed tomograpghy, ESRD = End stage renal disease, IEEE = Institute of Electrical and Electronics Engineers, MDCT = Multi Detector Computed Tomography, SCNN = Siamese Convolutional neural network.

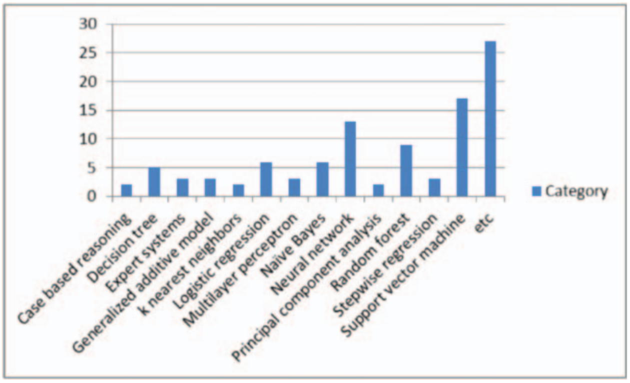

Figure 3. Machine-learning algorithms within the top-fifty most-cited articles. Various artificial intelligence algorithms are listed. Support vector machines, neural networks, and random forests are widely used. Of the 13 neural-network types, five were artificial neural networks and two were convolutional neural networks; the remaining were recurrent neural networks and sparse convolutional networks. The remaining algorithms used the following models: archetypal analysis, Bayesian belief network, Bayesian generalized linear network, C5.0 trees, efficient belief propagation, eXtreme gradient boosting, fitted Q iteration, generalized linear model, gradient boosting machine, Hessian-based difference of Gaussians, hierarchical clustering, ID3, kernel classifier, k-means, k-NN classifier, LIBSVM, linear discriminant analysis, manifold diffusion, Markov decision process, multitask temporal, Nguyen-Widrow initialization, polynomial linear model, Q learning, quadratic discriminant analysis, relevance vector machine, REVOLVER, and a variational Bayesian–Gaussian mixture model. ID3 = iterative dichotomiser, LIBSVM = library for support vector machines, REVOLVER = repeated evolution in cancer.

The AIs in most of these articles were based on supervised learning. Documented results and those gained from experience supported various types of decision-support systems.

For image analysis, computer-aided diagnosis (CAD) was applied. The key to CAD is the combination of medical and computer image processing to appreciate the image characteristics.[11] Kidney tumors are categorized as cancerous (clear cell, papillary, chromophobe, cystic renal cell carcinoma, Wilms tumor, etc.) and non-cancerous lesions (angiomyolipoma, oncocytoma, etc.). Kidney tumors are sometimes associated with genetic diseases. In addition, it is especially difficult to confirm the diagnosis using an invasive diagnostic method, such as biopsy because of its diagnostic yield rates and complications. Hence, knowing the kidney-tumor subtype is essential for deciding on a treatment plan. There were 11 tumor-related articles within the top fifty. Most of these articles dealt with cancer diagnosis using images. The remainder were about cancer proteomes and genes. Depending on the study characteristics, decision trees, support vector machines, sparse convolutional neural networks, multilayer perceptron, naïve Bayes, k-nearest neighbor, and belief propagation models were used as supervised learning means. Feature selection and extraction were used for dimensionality reduction. One study on cancer genes used a transfer-learning method called repeated evolution in cancer.[12]

The remaining topics included kidney anatomy, PKD, and renal pathology. Specifically, two articles were about kidney anatomy. A Hessian-based difference of Gaussians, as unsupervised learning, was used for finding glomeruli with magnetic resonance imaging. Quantitative image analysis and a support vector machine were used to detect hydronephrosis by means of supervised learning. Two articles dealt with PKD. The cyst size was measured using convolutional neural networks and semantic mapping as supervised learning, and feature extraction was used for dimensionality reduction.

For renal pathology, one article was about clustering renal transplant-rejection pathology with archetypal analysis and principal component analysis. The other was about CAD using Ratsnake,[13] a publicly available generic image-annotation tool, based on gradient vector-field[14] and boundary vector-field models.[15] In this field, other relevant generic image-annotation tools, for example, LabelMe, Photostuff, Phtocopain, K-space annotation tool, and graphic annotation tool, were nominated as other methods.

In general, machine learning has been applied to various problems in many studies, for example, classifying subjects, searching for associations between variables, finding objects with similar patterns, and predicting risks and results based on basic characteristics. In diagnostic and therapeutic areas, AIs can help to quickly detect risks, precisely predict prognoses, and enhance the accuracy of the final diagnoses to support proper management of diseases in various medical fields. The nephrology field is no exception.

As the kidneys play an important role in homeostasis, kidney diseases might be related to other organ disorders. At times, the opposite might occur, for example, systemic dysfunctions might affect kidney disorders. Most kidney diseases have complicated and overlapping multifactorial clinical phenotypes.[16] This could lead to mistakes and missed diagnoses, leading to late diagnoses and disease progression. In addition, the high prevalence and low awareness of kidney diseases sometimes make early diagnoses with intervention impossible, if the resources show inadequate features.[17] AIs can help physicians reduce these shortcomings and reinforce personalized medicine to help preserve the kidneys.

Our study has some limitations due to the bibliometric study itself. The results of a citation analysis can change depending on the research time. Moreover, it cannot reflect the most recent status, owing to lead-time bias. However, we can check the current status and trends of AI in nephrology and matters for nephrologists' concern during the last 30 years, through the top fifty most-cited articles. AIs' flexibility and learning capability can help clinicians' decision-making processes. Adequately used AI models allow for more plentiful data with reliable prediction of disease outcomes.

Compared to the past, interest in and studies about AI increased considerably during the 2010s. Previously, AI algorithms were investigated using relatively easy-to-access data, for example, radiologic images and laboratory results. A deeper and wider range of statistical and reference data will enable the use of AI in the diverse fields of nephrology. Currently, many nephrologists, bio-informaticists, and computer engineers are trying to develop more precise and concise AI models using novel advanced algorithms. These efforts will help improve kidney health in the near future. With this bibliometric analysis, the former common interest of AI such as AKI and tumor will be the source for concrete and accurate machine learning models that will be developed by many researchers. In addition, less highlighted items (CKD, kidney transplant, etc.) would be relatively good subjects for rising and new researchers.

Acknowledgments

We would like to thank Editage (www.editage.co.kr) for English language editing.

Author contributions

Conceptualization: Sihyung Park, Bong Soo Park, Kang Min Park.
Data curation: Sihyung Park, Bong Soo Park.
Formal analysis: Sihyung Park.
Investigation: Sihyung Park.
Methodology: Sihyung Park, Bong Soo Park.
Project administration: Sihyung Park, Kang Min Park.
Resources: Yoo Jin Lee, Il Hwan Kim, Jin Han Park, Junghae Ko, Yang Wook Kim.
Software: Yoo Jin Lee, Il Hwan Kim, Jin Han Park, Junghae Ko, Yang Wook Kim.
Supervision: Sihyung Park, Yang Wook Kim.
Writing – original draft: Sihyung Park.
Writing – review & editing: Sihyung Park.

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