Review Article

Industry 4.0 applications in medical field: A brief review

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ABSTRACT

Background: Industry 4.0 is an established reality that seems to fulfil various requirements of the medical field, with extensive research going on in this area. Thus, there is a need to understand how Industry 4.0 can be a useful paradigm to fulfil various requirements of medical field using different technologies.
Aim of this work: The purpose of this study is to understand the role of Industry 4.0 in the medical field and identify research status along with future applications.
Materials and methods: Research articles on Industry 4.0 in medical and related fields were studied to identify applications and research direction.
Result: Through this study, we identified different technologies, capabilities and research status of Industry 4.0 in the medical field. Furthermore, we have also identified 19 important applications of Industry 4.0 in the medical field to provide a significant contribution to the research and development of new medical models and devices. Industry 4.0 seems to be an essential part of tomorrow's medical field and smart factories, where software, technologies and processes provide efficient and world-class results with lesser time and cost.
Conclusion: Industry 4.0 shows the extensive capability of manufacturing of newly customised implants and innovative tools and instruments for the medical field. It provides a type of digital hospital and a complete monitoring system that fulfils the individual requirements of the patient/medical industry with optimised time and cost. Industry 4.0 is an innovative approach to generate new concept and undertake development in the medical field through the integration of technologies, smart machines and different software. Industry 4.0 manufactures high-quality, regulated medical devices which are highly customised as per patient requirements. This revolution embraces automation and creates new manufacturing opportunities in the medical world. With the help of the Internet of things (IoT) and the Internet of services (IoS), it creates a new virtual world. It creates connectivity and data exchange with the help of new manufacturing technologies, software, sensors, robots and other advanced information technologies. In future, Industry 4.0 can create new opportunities and innovative routes for patient care.

1. Introduction

Fourth Industrial Revolution is known as Industry 4.0, which is the concept of achieving faster innovation in manufacturing with increased efficiency in the supply chain. In the medical field, Industry 4.0 seems to provide extensive applications towards the creation of customised implants, tools and devices. This revolution provides a better way of using information, manufacturing and services to provide improved quality of life. Therefore, it provides new opportunities in manufacturing and extends the boundary of innovation through the application of the Internet of things (IoT) and the Internet of services.[1,2]

Industry 4.0 enhances the smart manufacturing system that helps to strategise support in manufacturing, medical and associated fields. It includes mobilisation of computing power that handles data and creates the ability to access data from anywhere. It consists of intelligent sensors which help to communicate machine processes, maximise production efficiency and minimise the cost.[3,4]

Industry 4.0 is the combination of the automation process, manufacturing units and smart machines. It consists of digitisation, IoT, internal connected network, human resources for supervision,

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  [b] https://scholar.google.co.in/citations?user=4047148AAAAJ&hl=en.

Supervisory Control and Data Acquisition (SCADA), robots for automation of many critical functions, valves, sensors, actuators, PLC system, communication protocols and cyber security. It uses artificial intelligence (AI) to share information digitally in hospitals and enables to create full visibility in operation that provides a higher level of information about quality, inventory, raw material, waste, output, assets and customer demand visibilities, help industries to save time and money and improve customer satisfaction. It creates a good relationship between the supplier and manufacturer.[5] Industry 4.0 has an extensive capability to fulfil varied requirements in medical and its associated fields. It uses AI by which machines and other technologies are programmed similar to human intelligence.[4,6]

Industry 4.0 connects products, smart materials and machines and generates data from many locations. This revolution is a self-managed production process in which both machines and products know about their capacities, state and configuration options to optimise production efficiency. It creates an intelligent and highly flexible manufacturing system. In the medical field, Industry 4.0 helps manufacture any customised implant as per the requirement of the individual patient with the help of different software and specific machining technologies. It meets the demands of personalised solution such as bioelectronic medicines, detection of glucose levels, electronic-based testing and next-generation inhalers.[7,8]

Industry 4.0 brings supplier and customer together in which production order is directly sent to the machine, facilitating the conversion of data into components. Complex customised products/parts can be manufactured easily in a fraction of time. It also reduces inventory by digitally storing the product/medical data.[9,10]

2. Evolution of industrial revolutions

Different industrial revolution evolutes in the following manner:

➢ *First Industrial Revolution*

The First Industrial Revolution started from the end of the 18th century (1760–1840), with the introduction of machines into the manufacturing. In this revolution, manual production is upgraded, and the industry tried creating comfort with the use of steam-powered engines. It greatly helped agriculture and also made extensive changes in the textile industry.

➢ *Second Industrial Revolution*

The Second Industrial Revolution dates between 1870 and 1914, with the introduction of railroads and telegraphs into industries. The primary aim of this revolution was to introduce mass production and bring upon innovation in chemistry and allied areas.

➢ *Third Industrial Revolution*

The Third Industrial Revolution is about the introduction of digital technologies in production systems, between 1950 and 1970. This revolution helped the transition from analogue to a mechanical system. There are huge developments in communication, computer and information technology (IT). It created a new level of automation of the manufacturing system by introducing flexible and customised production using different manufacturing technologies, which operates independently with the help of a computer.

➢ *Fourth Industrial Revolution*

The Fourth Industrial Revolution is anticipated from 2020 and is supposed to cater the future needs of the industry. This industrial revolution is highly dependent on innovations (disruptive) such as three-dimensional (3D) printing, AI, IoT and robotics. It may disrupt many business models, industry and the whole scenario. It refers to the development of processes in manufacturing and chain production. Industry 4.0 refers to a new style of production because it efficiently and effectively uses new techniques for manufacturing processes, by the combination of intelligent manufacturing machines. It creates a smart factory, by which customisation is efficiently undertaken.

3. Function of Industry 4.0 in the medical field

Industry 4.0 performs various functions and profits among all the previous revolution because it solves various medical problems with the interdisciplinary approach. It is a suitable industrial revolution for automation. It provides flexibility in design and manufacturing by which production system is digitally controlled.[1,7] Industry 4.0 is to perform the following functions when adopted in the medical field:

- Maximise productivity
- Analyse data of the patient which is helpful for different medical technologies
- Digitally store medical data and provide awareness about the next level of diseases
- Increase accuracy
- Reduce time and cost
- Improve quality
- Reduce inventory by storing patient data in the digital computed-aided design (CAD) file
- Reduce paperwork
- Improve material management
- Improve tooling management
- Efficiently manufacture customised implants as per patient match using sensor-based smart components
- Apply right control processes for complex surgeries
- By the applications of sensor system and digital technologies, it can automatically track new diseases
- Create a centralised information system in the hospital
- Detect data of the patient and determine relative information

Industry 4.0 can help innovation in the medical field to fulfil different requirements. It introduces new designing, development of customised tools and various other support devices in lesser time with optimised cost.

4. Need for the study

In medical field, customisation, lesser lead time and other surgical facilities are important issues that cannot be solved through traditional manufacturing technologies. For this, we require a smart manufacturing system that can be incorporated into Industry 4.0, and also it is a new approach to meet the required quality. Therefore, there is a need to undertake a study of different technologies and capabilities of Industry 4.0 in the medical field and identify the current status of research. Also, there are significant needs to identify its extensive applications in the medical field.

5. Significant technologies of Industry 4.0 for the medical field

Industry 4.0 helps to create digitisation in the medical field with the help of different technologies. These technologies provide safety, satisfaction and better information to the patient.[1,6] Different technologies of Industry 4.0 for medical field are discussed in the following paragraphs:

5.1. Additive manufacturing

Additive manufacturing is a disruptive innovation which is helpful in the medical field. It uses a set of 3D printing, 3D scanning technologies and associated designing and scanning software. It manufactures any medical/other physical parts layer by layer from 3D CAD data. In medical field, this is the most successful technology because of its flexibility in design and manufacturing. It manufactures exact patient-specific implants, tools and specific devices as per requirement.

5.2. Robotic

Robots are used to perform surgery and provide improved performance, movement and control. Now, surgery can be performed through computer control. It reduces/eliminates tissue trauma in open heart surgery case. It can also work in an environment that is felt dangerous for surgeons.

5.3. Holography

Holography is a noncontact 3D imaging that can be seen by a naked eye. It provides details of the human anatomy, tissue, bones and activity of an internal organ of the body with high resolution. Doctors can now see the patient in a holographic image without the physical presence of the patient. It is an excellent tool for contactless study which is used to measure the internal and external fracture. Holography has excellent potential to addresses the challenge of storing the complex issue of 3D image storing of the patient. Patient diseases/other information can be stored digitally which can be helpful to train medical students.

5.4. Sensors

In medical field, pressure sensors and mass flow sensors are used to provide a solution as per the requirement of surgery. Sensors provide information about temperature, blood pressure and other conditions of the patient. Different types of sensors are used as per the requirement of the medical field.

5.5. Internet of things

IoT has opened up a world of possibilities in medicine. It connects the Internet and medical devices and collects valuable information to provide control over patients' lives and treatment. It is helpful in monitoring, treatment and testing to provide satisfaction to the patient.

5.6. Big data

In health care, big data provides life-saving outcomes. By the digitisation, it referred to vast quantities of information and analysed it. Doctors required an understanding of patients' past for their best treatment, so this technology is helpful to provide valuable information regarding patients such as the sign of illness. It also provides relevant critical insights into better care and faster treatments.

5.7. Artificial intelligence

In medical field, AI is used to analyse complex medical data. It is an essential technology that is programmed and controlled by machines with the help of the computer. It has the ability to gain information and well-defined output to doctors and patients. AI provides prevention and treatment technique to improve patient outcome. It is helpful in personalised medicine, diagnosis processes, disease level, drug development and patient monitoring.

6. Different capabilities of Industry 4.0 in the medical field

Industry 4.0 could provide exciting capabilities and new opportunities for patient care. It individualises products with the precise manufacturing of patient-specific devices, which creates a high-quality result. It also positively impacts the hospital
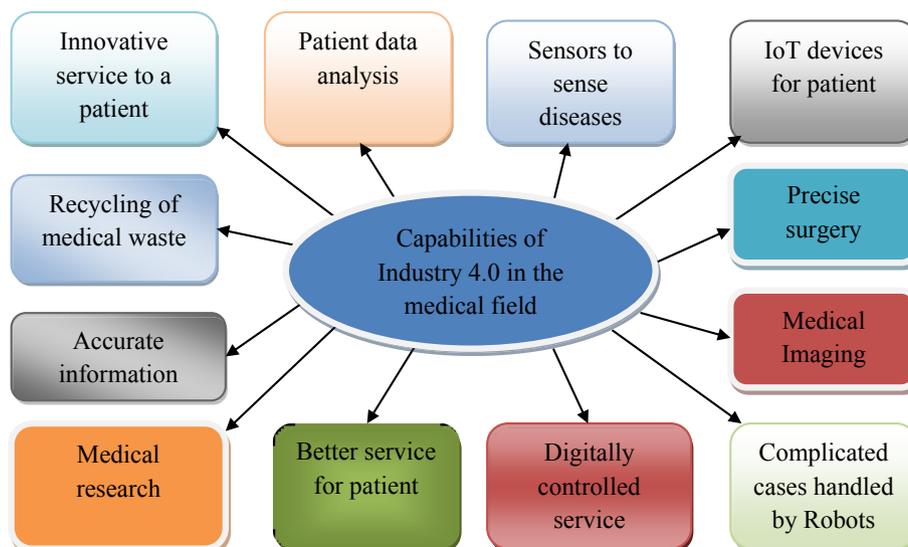

Fig. 1. Capabilities of Industry 4.0 in the medical field. IoT, Internet of things.

Table 1
Industry 4.0 applications in the medical field.

S No	Applications	Description	References
1	Customisation of implants	• The customisation is the primary requirement of the medical field because data of every patient-specific implants and devices are different • Industry 4.0 is famous because of the manufacturing of the customised product, so it can quickly create high-quality implants and devices in lesser time and cost	Stock and Seliger 2016[12]; Aceto et al, 2018[2]
2	Digital hospital	• Industry 4.0 provides better information management in medical by the application of IoT • Helpful in keeping medical record, physician, sample and laboratory identification • By the applications of digital technologies used in Industry 4.0, symptoms and cause of diseases are easily identified	Lobo, 2017[13]; Wang et al, 2017[14]; Kilic, 2016[15]
3	Smart implants	• Efficient manufacturing of smart medical components and the same can communicate with monitoring systems and remote physicians • It evolves in the part of the internet of service and opens a new era of opportunities in the medical field • By the applications of smart material, implants can change the shape with increase in temperature concerning time as per requirement	Jee and Kim, 2013[16]; Liu and Xu 2017[17]
4	Designing and manufacturing of surgical tools and devices	• Industry 4.0 can play a useful role in the design and production of implants, surgical tools, biomodels and all other medical devices and models in lesser time • Also used for upgradation of tools and devices by the application of additive manufacturing • Implants manufactured by smart manufacturing technology fit the patients comfortably	Zhong et al, 2017[18]; Javaid and Haleem 2018[19]
5	Management during a medical emergency	• During unusual circumstances such as critical illness or unavailability of any family members, technologies are reliable to easily identify previous medical history of the patient such as name, age, blood group, etc. • Provide more time for treatment by speedy admission procedure • Provides 3G video equipment in an ambulance by which doctors can also image the condition of the patient before admitting	Lobo, 2017[13]; Ramanayake et al, 2014[20]
6	Provides implants in lesser time	• Build a customised model in lesser time with required mechanical strength • Helpful to create a conceptual model for medical applications • By the applications of different advance designing and manufacturing technologies, implants and other medical devices are created in lesser time	Wollschlaeger et al, 2017[21]; Basl, 2017[22]
7	Cost-effective for the hospitals	• Produces any medical devices, instruments or implants at a lower cost • Digitally controls all the system in the hospital and provides excellent service to the patient • Highly reliable for manufacturing of a customised product which correctly fits the patient • A customised implant as per patient data reduces risk and surgery time	Bahga and Madisetti 2013[23]; Wang et al, 2016[24]

Table 1 (*continued*)

S No	Applications	Description	References
8	Improved accuracy as per patient match	• Models/parts manufactured by smart manufacturing technology have good accuracy and surface finish • Using good-quality material accuracy is improved • Provides satisfaction to the patient	Sommer, 2015[25]; Thuemmler and Bai 2017[1]
9	Multimaterial implants, tools and devices with excellent strength	• Smart manufacturing technology uses multimaterials as input material • Multimaterial-printed implants provide exact information such as defects in the bone of the patient • These multimaterial medical models help the surgeon for a better understanding of the patient-specific problem before surgery	Manogaran et al, 2017[7]; Haleem et al, 2018[6]
10	Provide flexibility	• Industry 4.0 provides excellent flexibility during a complicated surgery • Traces the cause of diseases by predicting data of different patients • Flexibility to create industrial parts, medical models, cultural artefacts and also other dental models	Brettel et al, 2014[26]; Theorin et al, 2017[27]
11	Improved research and development	• Industry 4.0 provides essential direction for the research and development of personalised prostheses and other implants/devices. • Industry 4.0 helps to efficiently manufacture a prototype, and this prototype is to be tested and used for research & development purposes	Sommer, 2015[25]; Stock and Seliger, 2016[12]
12	Precise for surgeons	• Medical parts and components manufactured by this process performed precise surgery because smart manufacturing system produces an exact fit model. • Easy handling of different complex cases	Basl, 2017[22]; Javaid and Haleem, 2018[8]
13	Improve communication	• Medical model manufactured by smart manufacturing systems can improve the communication between doctor/surgeon and patient. • Doctors and surgeons can better understand the treatment outcomes and provide appropriate information to the patient.	Zhong et al, 2017[18]; Aceto et al, 2018[2]
14	Reduces surgery risk	• Industry 4.0 uses sensors and innovative manufacturing technology which has the potential to reduce the surgery risk • Quickly identifies the problems for complicated cases • Performs surgery efficiently which increases the success rate of operation	Haleem et al, 2018[6]; Bahrin et al, 2016[28]; Branke et al, 2016[11]
15	Reduces inventory of implants	• Industry 4.0 is famous because of the customisation, which can manufacture any shape implant • Reduces inventory cost because implants are produced as per the individual demand • By the use of digitisation, it also reduces the paperwork because patient data are stored digitally	Ghobakhloo, 2018[29]; Hofmann and Rusch, 2017[30]; Hozdic, 2015[31]
16	Identifies the level of diseases	• By the use of different scanning process and technique, patient data are used efficiently • Helpful to identify different diseases and their causes by taking data from various patients • Also helpful to identify the level of diseases	Haleem et al, 2018[6]; Kamble et al, 2018[32]

Table 1 (*continued*)

S No	Applications	Description	References
17	Holography	• Industry 4.0 uses holography to display medical data of the whole patient in a three-dimensional tomographic image • Doctors can see patient data in multiangular view without the presence of the patient • Holography is an emerging and powerful tool for medical applications used in orthopaedics, pathology, tissue, dentistry, ophthalmology, otology, urology and cardiology	Mishra, 2017[33]; Haleem et al, 2018[6]
18	Virtual reality	• In medical, virtual reality can provide needful information to doctors and patients • Provides a 3D view of the patient's data • Improves the quality of surgical planning • Reduces planning time of complicated surgery • Provides surgical skills to surgeons using simulation and investigates each organ of the human body in a better way	Li et al, 2017[34]; Javaid and Haleem, 2018[35]; Ekstrand et al, 2018[36]; Zhang, 2018[37]
19	Complete monitoring	• Easily monitors the whole treatment process of the patient by recording all data • Helps to monitor and avoid public health problem with the help of different medical devices and technologies • Increases the quality of medical treatment with optimised management cost	Lobo, 2017[13]; Javaid and Haleem, 2018[38]; Kotevski et al, 2016[39]

management system with the help of innovative technologies.[1,11] In medical field, this revolution will become a new reality to create an innovative concept and stay competitive. It successfully changes the whole process of the medical field by the applications of new technologies. Fig. 1 shows the different significant capabilities of Industry 4.0 in the medical field.

Industry 4.0 provides innovative services to patients by analysing the data of the patient with the help of sensors and IoT. It provides accurate information using upcoming medical imaging techniques and helps perform precise surgery. It helps to easily handle different complicated cases with the help of a digitally controlled service to the patient. This revolution will readily undertake new research and development in the medical field. One of the excellent capabilities of this is the recycling of medical waste in the hospital that saves our environment. The new capabilities are well incorporated by Industry 4.0 in the medical field and help create excellent services to patients and doctors.

7. Research status on Industry 4.0 in the medical field

Research on Industry 4.0 in the medical field is an upcoming agenda. Obtaining data from Scopus by searching keywords such as 'Industry 4.0' and 'medical' gave a result of 70 research articles published in this field. In 2013, a single article published on Industry 4.0 in the medical field, but in the year 2014 and 2015, no articles were published. Six articles in 2016 and 14 articles in 2017 were published. In last year 2018, there was some increment in publications; 34 articles were published. In this year, until March 2019, 15 research articles have been published so far.

Journals and associated academic sources have published articles on 'Industry 4.0 in the medical field', such as communications in computer and information science journal and lecture notes in computer science including subseries lecture notes in AI and lecture notes in bioinformatics published as two articles each. Rest other sources and other journals published one article each in this field. Article source includes *Advances in Intelligent Systems and Computing*; *Advances in Production Engineering and Management*; *Chinese Journal of Mechanical Engineering* (English Edition); *Future Generation Computer Systems*; *IEEE Internet of Things Journal*; *IEEE Journal of Biomedical and Health Informatics*; *IFIP Advances in Information and Communication Technology*; *Journal of Industrial Information Integration*; *Journal of Network and Computer Applications*; *Manufacturing Chemist*; *Technological Forecasting and Social Change*; *Manufacturing Letters* and *Wireless Communications and Mobile Computing*.

In area-wise research on Industry 4.0 in medical, we observed that the computer science area provides the maximum contribution of 31% in total research publications. However, the overall engineering field contributes 25%; decision sciences and mathematics contributing 11% each; business, management and accounting 6%; materials science 4%; biochemistry, genetics and molecular biology 2% and other fields 10%, which includes energy, health professions, pharmacology, toxicology and pharmaceutics, physics and astronomy, psychology and social sciences.

From Scopus data, we have analysed that research on Industry 4.0 in the medical field is increasing and research and development are progressing towards providing commercially viable and acceptable solutions for the medical field.

8. Industry 4.0 applications in the medical field

Production of medical devices and implant is a big challenge for any manufacturer because every patient part/data differs. Therefore, this requirement of customisation can be quickly fulfilled by Industry 4.0 by using smart manufacturing machines and information technologies. Table 1, discusses various applications of Industry 4.0 in the medical field.

Implants create their intelligence and program as per the requirement of the individual patient. This intelligent manufacturing system fulfils the requirement of customisation in the medical field as per requirement. There is a requirement to solve the issue of general health. Industry 4.0 provides extensive opportunities to enhance digital manufacturing and efficiently solve all the important problems. In future, the Fifth Industrial Revolution called Industry 5.0 will take place and provide more advancement in engineering and medical field.[40] In future, Industry 5.0 will be introduced in the medical field to create mass personalisation by some additional technologies such as emergent AI, Internet of everything (IoE), digital ecosystem and complex adaptive system.

9. Discussion

In the medical field, Industry 4.0 focuses on the design and manufacturing and helps perform different cases precisely. It is used for manufacturing of customised medical implants, tools and other devices to meet the varied requirement of the individual patient. It can efficiently solve the problem by the application of its various components which helps to meet the requirements of the medical field. Industry 4.0 provides extensive contributions in the medical field with the help of innovative designing and smart manufacturing system. It efficiently manufactures complex shape medical implants with a wide variety of materials that make surgeon job easier with minimum risk. Surgeons and doctors can convert a need/idea into reality which provides a comprehensive opportunity for the manufacturing of modified medical implant as per requirement of the patient. To save cost and time of surgery, it enhances the opportunities to create a new innovative medical product which can also be helpful for research & development purposes. Industry 4.0 provides excellent flexibility to create smart industrial and medical models which help to improve communication between doctors and patients. It uses the innovative concept of holography and virtual reality. It reduces risk and analyses the data of the patient to increase the overall performance. Industry 4.0 uses different innovative devices that can quickly detect the glucose, sugar and cholesterol level of the patient.

10. Future scope

In future, Industry 4.0 will show opportunities for innovation using integrated innovative design, manufacturing and services. During research and development, it will play a significant role to achieve the requirement of medical. In future, Industry 4.0 will move towards mass production systems and adapt to the world-class manufacturing system. It enables to create smarter medical products in lesser time and cost. This revolution will change all management and treatment system of the patient. With the help of smart manufacturing technologies, medical students can be well trained to detect problems and correlate them to take future action. With the help of smart technologies, data from different patients are collected and analysed. Industry 4.0 offers new opportunities that create innovations by bringing new tools, devices and implants as per patient match. Different challenges regarding price, speed and complexity can be easily solved. The hospital will also change its way to purchase different tools and devices. By the use of the different device, it can monitor calorific intake. It can become a new path that helps to treat an illness such as diabetes, asthma and arthritis.

11. Conclusion

Industry 4.0 strongly encourages smart manufacturing and information system by which medical field can take significant advantage of this new revolution. It produces high-quality medical devices and components using advanced manufacturing techniques to meet the demand of each patient. In the medical field, it can help to increase overall performance by providing a digitally controlled management system to the patients. It effectively adopts mass customisation which fulfils the primary requirements. This revolution has a better impact on the environment by reducing wastage of material and human efforts with the help of various advanced manufacturing facilities. It provides precise surgery to the patient by the applications of additive manufacturing, sensors, holography, robots, AI, big data and IoT devices. There are various unique requirements for fulfilled Industry 4.0, such as bringing upon innovation with the help of holography and visual reality. Doctors and surgeons can take advantages of this revolution for research, development and excellent service to the patient. In the upcoming years, it will provide disruptive innovations to the medical field.

Conflicts of interest

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cmrp.2019.04.001.

References

1. Thuemmler C, Bai C. *Health 4.0: Application of Industry 4.0 Design Principles in Future Asthma Management*. In: *How Virtualization and Big Data are Revolutionizing Healthcare*. 2017:23–37.
2. Aceto G, Persico V, Pescape A. The role of Information and communication technologies in healthcare: taxonomies, perspectives, and challenges. *J Netw Comput Appl.* 2018. https://doi.org/10.1016/j.jnca.2018.02.008.
3. Pereira T, Barreto L, Amaral A. Network and information security challenges within Industry 4.0 paradigm. *Procedia Manuf.* 2017;13:1253–1260.
4. Luthra S, Mangla SK. Evaluating challenges to Industry 4.0 initiatives for supply chain sustainability in emerging economies. *Process Saf Environ Protect.* 2018. https://doi.org/10.1016/j.psep.2018.04.018.
5. Quezada LE, da Costa SEG, Tan KH. Operational excellence towards sustainable development goals through Industry 4.0. *Int J Prod Econ.* 2017;190:1–2.
6. Haleem A, Javaid M, Vaishya R. Industry 4.0 and its applications in orthopaedics. *J Clin Orthop Trauma.* 2019;10(3):615–616.
7. Manogaran G, Thota C, Lopez D, Sundarasekar R. *Big Data Security Intelligence for Healthcare Industry 4.0*. In: *Cybersecurity for Industry 4.0*. vol. 715. 2017: 103–126.
8. Javaid M, Haleem A. Additive manufacturing applications in orthopaedics: a review. *J Clin Orthop Trauma.* 2018;9(3):202–206.
9. Haleem A, Javaid M. 3D scanning applications in medical field: a literature-based review. *Clin Epidemiol Global Health.* 2018. https://doi.org/10.1016/j.cegh.2018.05.006. [In press].
10. Lee J, Bagheri B, Kao HA. A cyber-physical systems architecture for industry 4.0-based manufacturing systems. *Manuf Lett.* 2015;3:18–23.
11. Branke J, Farid SS, Shah N. Industry 4.0: a vision for personalised medicine supply chains? *Cell Gene Ther Insights.* 2016;2(2):263–270.
12. Stock T, Seliger G. Opportunities of sustainable manufacturing in industry 4.0. *Procedia CIRP.* 2016;40:536–541.
13. Lobo FA. *Industry 4.0: Redefining Manufacturing of Future Medical Devices*. ECN; 2017. https://www.ecnmag.com/article/2017/10/industry-40-redefining-manufacturing-future-medical-devices.
14. Wang S, Wan J, Zhang D, Li D, Zhang C. Towards smart factory for Industry 4.0: a self-organised multi-agent system with big data-based feedback and coordination. *Comput Netw.* 2016;101:158–168.

15. Kilic T. Digital hospital; an example of best practice. *Int J Health Sci Res Policy*. 2016;1(1):52—58.
16. Jee K, Kim GH. Potentiality of big data in the medical sector: focus on how to reshape the healthcare system. *Healthc Inform Res*. 2013;19(2):79—85.
17. Liu YK, Xu X. Industry 4.0 and cloud manufacturing: a comparative analysis. *J Manuf Sci Eng*. 2017;139(3):1—8.
18. Zhong TY, Xu X, Klotz E, Newman ST. Intelligent manufacturing in the context of industry 4.0: a review. *Engineering*. 2017;3:616—630.
19. Javaid M, Haleem A. Additive manufacturing applications in medical cases: a literature-based review. *Alexandria J Med*. 2018;54(4):411—422.
20. Ramanayake RPJC, Ranasinghe S, Lakmini S. Management of emergencies in general practice: role of general practitioners. *J Family Med Prim Care*. 2014;3(4):305—308.
21. Wollschlaeger M, Sauter T, Jasperneite J. The future of industrial communication: automation networks in the era of the internet of things and industry 4.0. *IEEE Ind Electron Mag*. 2017;11(1):17—27.
22. Basl J. Pilot study of readiness of Czech companies to implement the principles of Industry 4.0. *Manag Prod Eng Rev*. 2017;8(2):3—8.
23. Bahga A, Madisetti VK. A cloud-based approach for interoperable electronic health records (EHR's). *IEEE J Biomed Health Inf*. 2013;17(5):894—906.
24. Wang ZG, Zhang L, Wen-Jun Zhao WJ. Progress in digital medicine. *Chin J Traumatol*. 2017 Oct;20(5):297—298.
25. Sommer L. Industrial revolution-industry 4.0: are German manufacturing SMEs the first victims of this revolution? *J Ind Eng Manag*. 2015;8(5):1512—1532.
26. Brettel M, Friederichsen N, Keller M, Rosenberg M. How virtualisation, decentralisation and network building change the manufacturing landscape: an industry 4.0 perspective. *Int J Mech Ind Sci Eng*. 2014;8(1):37—44.
27. Theorin A, Bengtsson K, Provost J, et al. An event-driven manufacturing information system architecture for Industry 4.0. *Int J Prod Res*. 2017;55(5):1297—1311.
28. Bahrin MAK, Othman MF, Nor NH, Azli MFT. Industry 4.0: a review on industrial automation and robotic. *J Teknol*. 2016;78:137—143.
29. Ghobakhloo M. The future of manufacturing industry: a strategic roadmap toward Industry 4.0. *J Manuf Technol Manag*. 2018;29(6):910—936.
30. Hofmann E, Rusch M. Industry 4.0 and the current status as well as prospects on logistics. *Comput Ind*. 2017;89:23—34.
31. Hozdic E. Smart factory for industry 4.0: a review. *Int J Modern Manuf Technol*. 2015;7(1):28—35.
32. Kamble SS, Gunasekaran A, Gawankar SA. Sustainable industry 4.0 framework: a systematic literature review identifying the current trends and future perspectives. *Process Saf Environ Prot*. 2018;117:408—425.
33. Mishra S. Hologram the future of medicine — from Star Wars to clinical imaging. *Indian Heart J*. 2017;69(4):566—567.
34. Li L, Yu F, Shi D, et al. Application of virtual reality technology in clinical medicine. *Am J Transl Res*. 2017;9(9):3867—3880.
35. Javaid M, Haleem A. Current status and challenges of Additive manufacturing in orthopaedics: an overview. *J Clin Orthop Trauma*. 2019;10(2):380—386.
36. Ekstrand C, Jamal A, Nguyen R, Kudryk A, Mann J, Mendez I. Immersive and interactive virtual reality to improve learning and retention of neuroanatomy in medical students: a randomised controlled study. *CMAJ Open*. 2018;6(1):103—109.
37. Zhang L. *Applications of the Internet of Things in the Medical Industry (Part 1): Digital Hospitals*. IoT Zone; 2018. https://dzone.com/articles/applications-of-the-internet-of-things-in-the-medi-1.
38. Javaid M, Haleem A. 4D printing applications in medical field: a brief review. *Clin Epidemiol Global Health*. 2018. https://doi.org/10.1016/j.cegh.2018.09.007. [In press].
39. Kotevski A, Koceska N, Koceski S. E-health monitoring system. In: *International Conference on Applied Internet and Information Technologies*. 2016. https://doi.org/10.20544/AIIT2016.32.
40. Haleem A, Javaid M. Industry 5.0 and its applications in orthopaedics. *J Clin Orthop Trauma*. 2018. https://doi.org/10.1016/j.jcot.2018.12.010. [In press].