ORIGINAL ARTICLE
Biomedical Engineering

JKMS

https://doi.org/10.3346/jkms.2017.32.12.1938 • J Korean Med Sci 2017; 32: 1938-1946

Adapter-based Safety Injection System for Prevention of Wrong Route and Wrong Patient Medication Errors

Yong Chan Cho,[1]* Seung Ho Lee,[2]* Yang Hyun Cho,[3] and Young Bin Choy[1,2,4]

[1]Interdisciplinary Program in Bioengineering, Seoul National University College of Engineering, Seoul, Korea; [2]Institute of Medical & Biological Engineering, Medical Research Center, Seoul National University College of Medicine, Seoul, Korea; [3]Department of Thoracic and Cardiovascular Surgery, Samsung Medical Center, Sungkyunkwan University School of Medicine, Seoul, Korea; [4]Department of Biomedical Engineering, Seoul National University College of Medicine, Seoul, Korea

*Yong Chan Cho and Seung Ho Lee contributed equally to this work.

Received: 1 June 2017
Accepted: 27 August 2017

Address for Correspondence:
Young Bin Choy, PhD
Department of Biomedical Engineering, Seoul National University College of Medicine, 103 Daehak-ro, Jongno-gu, Seoul 03080, Korea
E-mail: ybchoy@snu.ac.kr

Funding: This work was funded by a grant from the Korea Healthcare Technology R & D Project, Ministry for Health, Welfare & Family Affairs, Korea (HI15C1087).

Wrong-route or -patient medication errors due to human mistakes have been considered difficult to resolve in clinical settings. In this study, we suggest a safety injection system that can help to prevent an injection when a mismatch exists between the drug and route or patient. For this, we prepared two distinct adapters with key and keyhole patterns specifically assigned to a pair of drug and route or patient. When connected to a syringe tip and its counterpart, a catheter injection-port, respectively, the adapters allowed for a seamless connection only with their matching patterns. In this study, each of the adapters possessed a specific key and keyhole pattern at one end and the other end was shaped to be a universal fit for syringe tips or catheter injection-ports in clinical use. With the scheme proposed herein, we could generate 27,000 patterns, depending on the location and shape of the key tooth in the adapters. With a rapid prototyping technique, multiple distinct pairs of adapters could be prepared in a relatively short period of time and thus, we envision that a specific adapter pair can be produced on-site after patient hospitalization, much like patient identification barcodes.

Keywords: Medication Error; Syringes; Catheters; Printing; Three-Dimensional

INTRODUCTION

Wrong-route or wrong-patient medication errors occur when the medication is injected into a wrong injection route or patient, respectively (1-5). These errors account for 12%–25% of the total drug medication errors occur in the hospitals worldwide (6-9), and they can result in life-threatening conditions and possibly patient fatality (7,10-16). In an attempt to reduce the possibility of such medication errors, several strategies have been developed. Most of these strategies involve educational programs for medical staff using error prevention manuals or route-specific barcode systems (15,17-19). While these strategies might help recognize and confirm route of medication, they still do not tackle the fundamental issues of human error. For example, even if a human mistake is discovered, you must still handle the issue of the wrong drug being injected. For this reason, Wrong-route and wrong-patient medication errors still remain a serious problem in clinical settings (2,15,18-22).

When a patient is admitted to a hospital, a catheter is usually connected to the vein of the patient first, with an injection port exposed outside of the body. After establishing the required medical prescription for the patient, the medical staff injects the required drug by connecting a syringe tip to the injection-port in the catheter. Understanding this procedure and in an attempt to prevent wrong medication errors, we suggest a safety injection system that can physically prevent the connection of a syringe tip to a catheter injection-port when there is a mismatch between a drug and patient or route. As part of this system, we propose adapters to be installed to syringe tips and catheter injection-ports, serving as a key and keyhole, respectively. Each pair of key and keyhole possesses a shape pattern specific to a matching pair of drug and patient or route. In this way, even when a medical staff is not aware of the medication error by mistake, a mismatch will be present to not allow the connection between the syringe tip and the catheter injection-port, thereby leading to automatic prevention of injection.

We envision producing the adapters with a specific key and keyhole immediately after patient hospitalization, similar to patient identification barcodes in clinical settings (20,21). In order for such a design to be applicable to a large number of pa-

pISSN 1011-8934
eISSN 1598-6357

tients visiting the hospital, it would be advantageous to fabricate the adapters in a relatively short time. For this reason, rapid prototyping (RP) can be an ideal solution over other conventional fabrication methods (23-26). The RP technique would allow for rapid, on-demand and on-site production of the adapters with various key and keyhole shape patterns, each customized to a specific patient or injection route. To test the feasibility of our strategy, we employed a Polyjet printing technique to fabricate the adapters in this work (25). Considering their medical use, the adapters herein were printed with a biocompatible material that is known to meet the United States Pharmacopeia (USP) class VI biocompatibility test (27,28).

MATERIALS AND METHODS

Adapter design

The safety injection system consists of two distinct adapters, i.e., the syringe and catheter adapters, to be connected to a syringe tip and catheter injection-port, respectively (Fig. 1A). We designed the syringe and catheter adapters to be equipped with a key and keyhole, respectively. For a syringe adapter, a specific male key pattern is embossed at one end, while the other end is shaped to allow for seamless fitting to the syringe tip. The catheter adapter is designed to have a female keyhole pattern at one end to be matched with a pairing syringe adapter while the other end is shaped to allow for seamless fitting to the catheter injection-port. We used the syringe tip and catheter injection-port with luer lock as exemplary devices in clinical use (Norm-ject® 10 mL disposable luer lock syringe, Henke Sass Wolf, Tuttlingen, Germany; and Q-Syte™ catheter extension set, Becton, Dickinson and Company, Franklin Lakes, NJ, USA), where the adapters are shaped accordingly. For both adapters, a marker is prepared as a reference for their alignment.

The operation scheme of the safety injection system is depicted in Fig. 1B. At the time of injection, the two adapters are aligned using the reference markers and insertion is attempted. When the drug matches the patient or route, the adapters have the corresponding shape patterns as key and keyhole, allowing the syringe tip to be inserted, forming a proper luer lock connection with the catheter adapter to allow for a seamless flow-path towards the catheter injection-port. When there is a mismatch, the adapters cannot be properly coupled, which physically hinders the luer lock connection between the syringe tip and catheter adapter, denying the flow-path towards the catheter injection-port.

In order to realize this, we suggest the following design, as shown in Fig. 2. The syringe adapter is in shape of a cylinder with a key pattern, 2 mm in height, which is embossed at one end. The inner diameter of the syringe adapter is 9.8 mm for its slip fitting to the syringe tip. The wall thickness of the cylindrical syringe adapter is 1.9 mm, giving it an outer diameter of 13.6 mm (Fig. 2A). The catheter adapter is in the shape of a cylindrical barrel with a keyhole pattern, 2 mm in height, that is engraved at one end. To allow for the smooth slip insertion of the syringe adapter, the inner diameter of the catheter adapter is made to be 14.2 mm, which is slightly larger than the outer diameter of the syringe adapter (13.6 mm). The outer diameter of the catheter adapter is 22 mm, which includes the keyhole pattern height and wall thickness. When a key and keyhole match, the catheter adapter allows for seamless fitting to the syringe tip and thus, a female luer lock copied from the catheter injection-port is prepared at the end. At the opposing end, a male luer lock copied

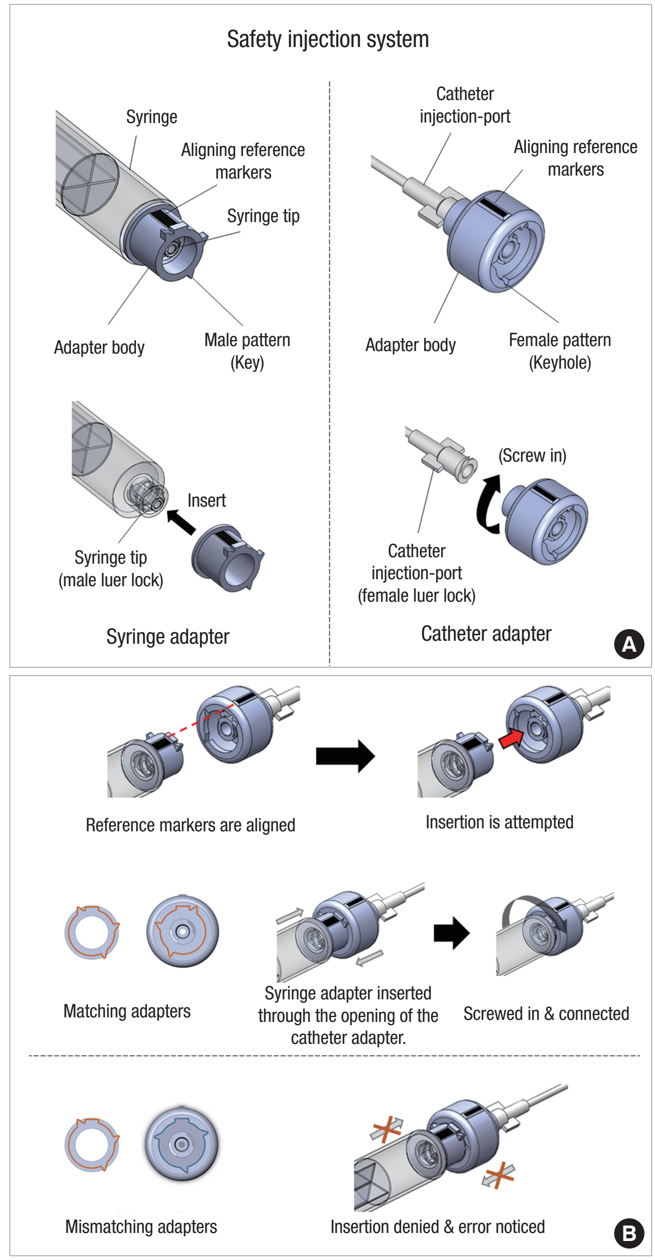


Fig. 1. Safety injection system. (**A**) Detailed schematic of safety injection system and (**B**) operational schematic of safety injection system.

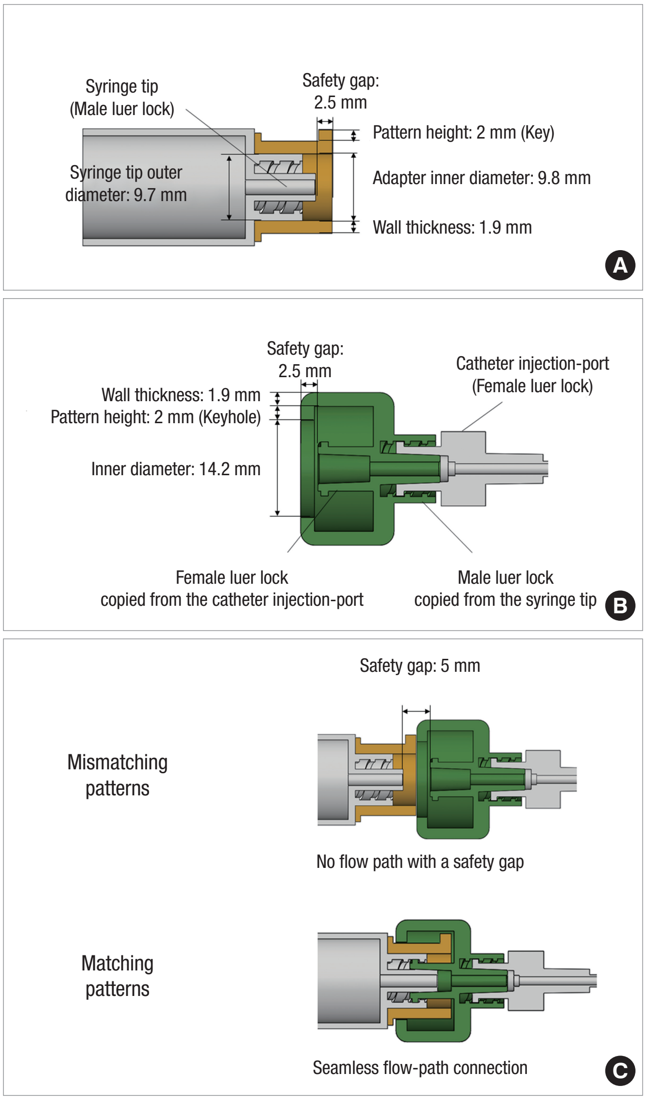


Fig. 2. Adapter design for safety injection system. (**A**) A syringe adapter, (**B**) a catheter adapter, and (**C**) their connections under the matching and mismatching conditions.

from the syringe tip is prepared to be fitted to the catheter injection-port (Fig. 2B).

Each adapter includes a safety gap (2.5 mm) made at the end where the key and keyhole patterns are present (Fig. 2A and 2B). This feature allows the male luer lock of the syringe tip and the female luer lock of the catheter adapter to remain 5 mm apart, even when a forceful attempt is made to connect a mismatching pair of adapters. This safety gap denies a flow-path to be made between the syringe and the catheter injection-port. Yet, when the key and keyhole patterns match, the syringe adapter can easily be slipped into the catheter adapter, allowing the syringe tip to screw into the female luer lock made in the catheter adapter (Fig. 2C).

3D scanning of syringe tip and catheter injection-port

In this work, we designed the syringe adapter to be connected

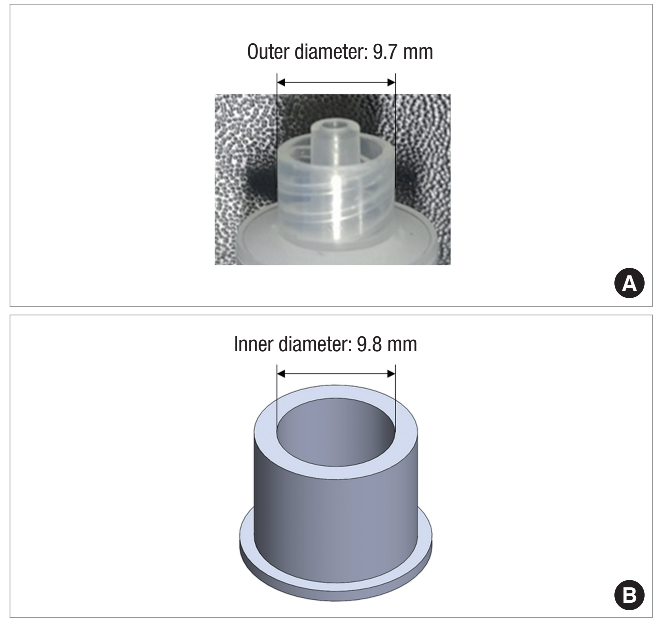


Fig. 3. Design of the syringe adapter. (**A**) Optical image of the syringe tip and (**B**) the corresponding 3D model of the syringe adapter.

to the syringe tip via a simple slip fitting. The syringe adapter was designed in the shape of a cylinder, having an inner diameter similar to the outer diameter of the syringe tip (Fig. 3). Yet, in the case of the catheter adapter, accurate shapes and dimensions were needed for the luer locks of the syringe tip and the catheter injection-port. To accomplish this, we imaged both the luer locks of the syringe tip and the catheter injection-port using a 3D scanner (Ultra HD, NextEngine, Inc., Santa Monica, CA, USA). In order to scan the inside of the syringe tip, the tip was first cut to expose its cross-section, showing the internal thread and slip tip (Fig. 4A). During scanning, the syringe tip and catheter injection-port were each placed on a turntable to be rotated 360° in front of the scanner. The scanned images obtained at each of the rotating angles, in 10° increments, were stacked to reconstruct the 3D contour of the object. The images were then post-processed using Autodesk Meshmixer (Autodesk, Mill Valley, CA, USA) and Meshlab (Slashdot Media, La Jolla, CA, USA) (Fig. 4B). The resulting images were exported in stereolithography file format (.stl) and imported into SolidWorks (Dassault Système SOLIDWORKS, Waltham, MA, USA).

We then measured the dimensions of each part of the syringe tip and catheter injection-port referenced from the scanned images. For the internal thread of the syringe tip, the outer diameter, height, lead and thread thickness were measured (Fig. 4C). For the slip tip, the height and outer diameters of the top and bottom were measured. For the catheter injection-port, the height, lead, inner diameters of the top and bottom, and thicknesses of the head and thread were measured (Fig. 4C). Based on those dimensions, we reconstructed the 3D models of the syringe tip and catheter injection-port, as shown in Fig. 4D, which

 https://doi.org/10.3346/jkms.2017.32.12.1938

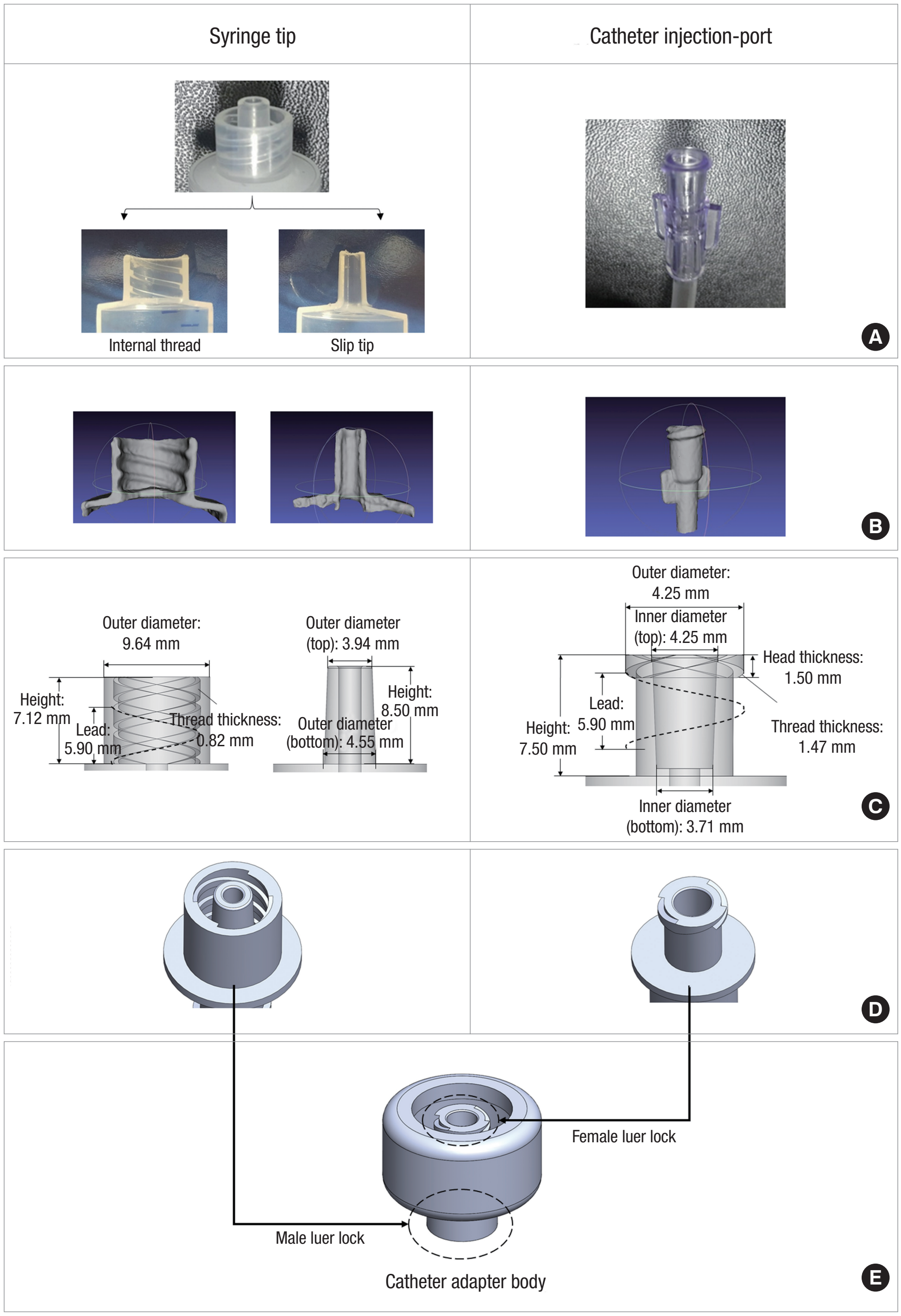


Fig. 4. Design of the catheter adapter. (**A**) Optical images of the syringe tip and catheter injection-port, and their corresponding (**B**) 3D-scanned images and (**C**) re-drawn cross-section images showing the measured dimensions. (**D**) 3D-reconstructed images obtained with the syringe tip and catheter injection-port. (**E**) 3D model of the catheter adapter.

were then combined to make a model for the catheter adapter, as shown in Fig. 4E.

Pattern and code generation for key and keyhole

Fig. 5 depicts the strategy used to generate a specific shape pattern for the key and keyhole pairs. To construct the key shape pattern, we first generated a specific code based on three distinct criteria: region, position, and shape. For the region code, we divided the periphery of the circular end of the adapter into three regions of equal lengths from the location of the reference tooth (Fig. 5A). At each region, we located ten distinct, equally spaced positions to generate the position codes from 0 to 9 (Fig. 5B). At each position, a tooth was placed having one of three distinct shapes, i.e., the right-skewed, isosceles and left-skewed

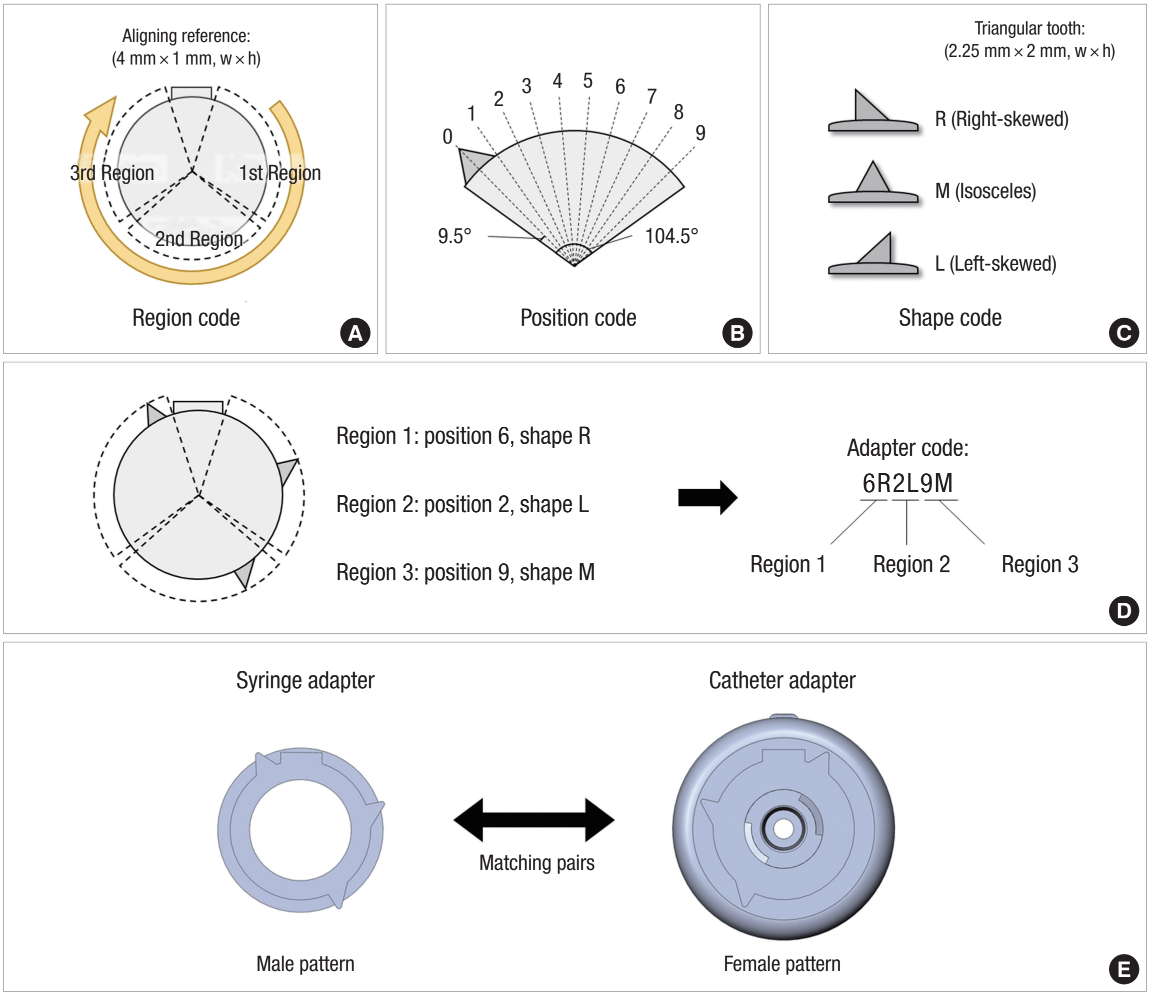


Fig. 5. Scheme for pattern and code generation. (**A**) Region code: three regions are assigned through the periphery of the circular end of the adapter. (**B**) Position code: ten distinct positions are assigned in each region. (**C**) Shape code: three distinct shapes of a tooth are assigned to be located in each position. (**D**) Example pattern and its corresponding code in the syringe adapter. (**E**) Example matching patterns formed in the syringe and catheter adapters.

triangles representing the shape codes of R, M, and L, respectively (Fig. 5C).

As shown in the example key pattern (Fig. 5D), the code was composed of six discrete digits, where the first, middle and last two digits each represented the codes from regions 1, 2, and 3, respectively. For each two-digit code, the first and last digits represent the position and shape of the tooth, respectively. The key and keyhole patterns were then embedded into the 3D models of the syringe and catheter adapters, respectively. Fig. 5E shows an example of the final 3D models of the syringe and catheter adapters containing the key and keyhole patterns, respectively. In order to be matched via a serial connection, a keyhole pattern for the catheter adapter was prepared by using a mirror image of the key pattern for the syringe adapter.

Adapter fabrication

The final 3D models of the adapters were converted to a stereolithography file format, and imported to a Polyjet 3D printer (Projet® 3510 SD, 3D Systems, Valencia, CA, USA). For efficient production, multiple adapters were integrated into a single file (Supplementary Fig. 1). We used Visijet M3 Crystal® (3D Systems) as the composing material, which is known to be highly biocompatible (USP class VI) (27,28).

RESULTS

Adapter characterizations

Using the scheme for code generation presented in this study, there could be 27,000 distinct combinations of adapter pairs;

$$\text{Number of combinations} = (\text{number of position} \times \text{number of shape})^{\text{number of region}} = (10 \times 3)^3 = 27{,}000$$

Among those possible combinations, Fig. 6 shows 36 different adapter pairs prepared in this work. The total time for their fabrication was 3.5 hours. Fig. 7A and 7B show the 3D models and their corresponding optical images of one of the adapter pairs herein (code: 6R2L9M), respectively. The products were

 https://doi.org/10.3346/jkms.2017.32.12.1938

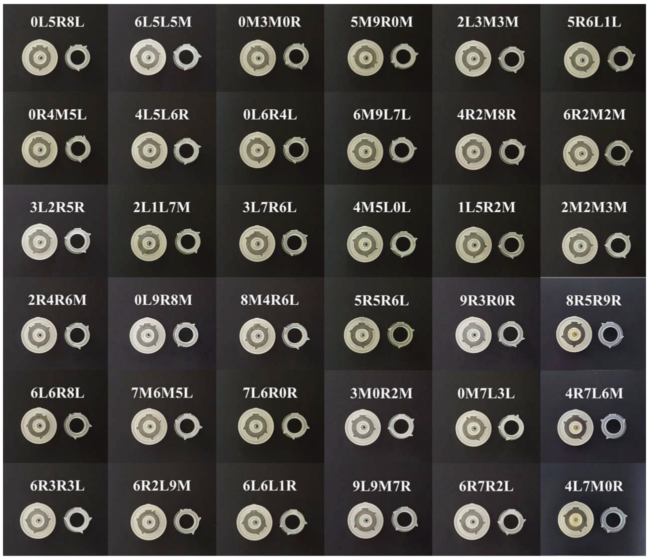


Fig. 6. Adapter pairs of 36 distinct codes prepared in this study.

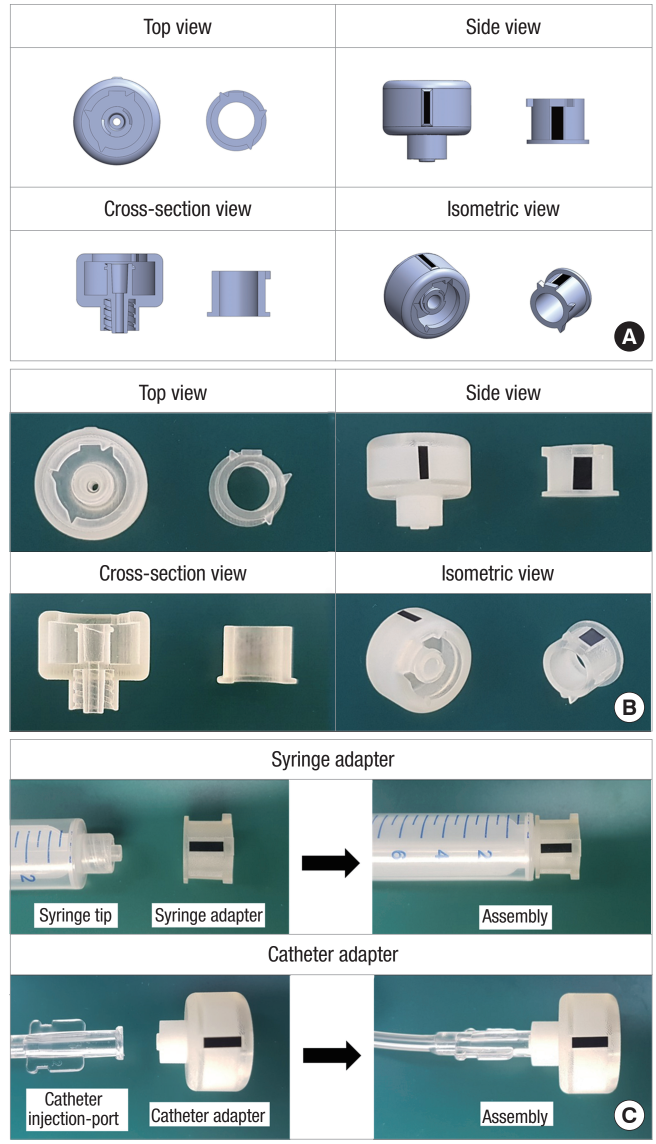


Fig. 7. Adapter characterizations. (**A**) 3D models and (**B**) their corresponding optical images of the example adapter pairs (code: 6R2L9M). (**C**) Assembly of the adapters with a syringe tip and catheter injection-port.

fabricated following the models without noticeable defects, particularly in the cross-section of the catheter adapter, where the male and female luer locks were seen to be properly formed. In addition, it should be noted that the critical dimensions of the constituents, such as the lead and thread, were retained as constructed in the 3D models. This supports the case that the adapters could be accurately assembled with the syringe tip and catheter injection-port employed in this study with no noticeable hindrance or fracture (Fig. 7C).

Performance of the safety injection system

In order to assess the performance of the safety injection system proposed herein, we first used a matching pair of syringe and catheter adapters, where the code, 6R2L9M, was simply employed as an example (Fig. 8A). The adapters were first assembled with a syringe tip and catheter injection-port, and the connection of both adapters was attempted as shown in Fig. 1B. According to our observations, the matching key and keyhole patterns allowed for the syringe adapter to advance forward through the 5 mm safety gap, so that the syringe tip could be screwed into the male luer lock formed in the catheter adapter, as depicted in Fig. 2C. To implement the scenario of the mismatched pair, we used syringe and catheter adapters with differing codes: the syringe adapter with the code, 4L5L6R and the catheter adapter with the code, 6R2L9M (Fig. 8A). In this exemplary case, when the connection of both adapters was attempted, the syringe adapter could not be inserted into the catheter adapter and thus, due to the presence of the safety gap, the syringe tip could not approach the male luer lock in the catheter adapter (Fig. 2C). To further confirm this rejection scenario, we also tested the example of the mismatched pair with the only difference in shape of a single tooth. For this, we prepared the syringe adapter with the code, 4L5L6M and the catheter adapter with the code, 4L5L6R. Our result revealed that with this extreme condition again, the pairs could not be properly connected (Fig. 8A).

To simulate the medication injection, the syringe was filled with an aqueous dye solution (fluorescein), which was injected under both matching and mismatching conditions (Fig. 8B). For the matching pairs of the adapters, it was observed that the solution could be transferred into the catheter without any apparent leak. On the other hand, when the adapter pairs mismatched and the connection was not made, the solution leaked into the gap between the two adapters and no solution was observed in the catheter. This result suggested that even when the

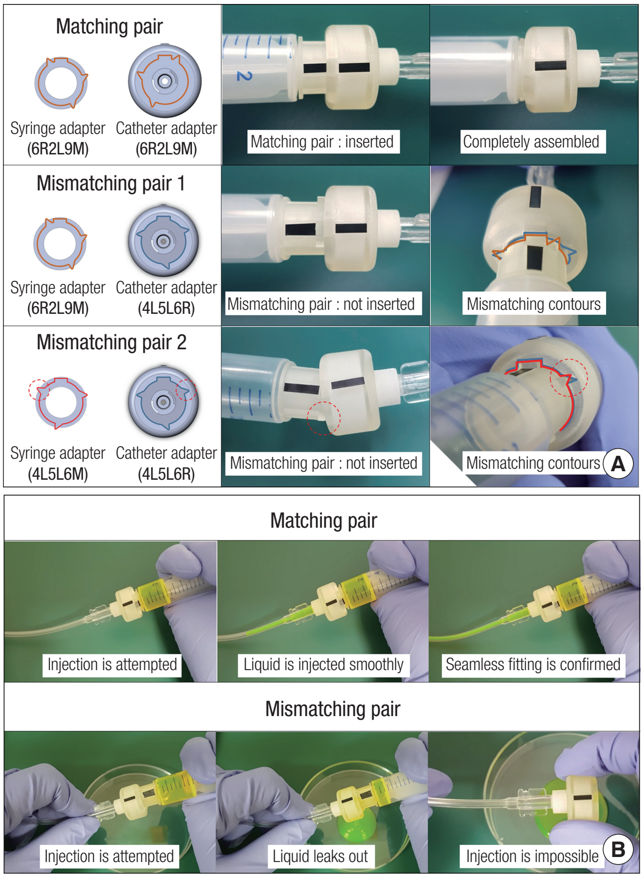


Fig. 8. Performance of the safety injection system. (**A**) Connections of the adapters under the matching and mismatching conditions and (**B**) liquid injection under the matching and mismatching conditions.

injection was physically attempted by mistake, the medication could not be delivered into the catheter with the mismatching adapter pairs, and hence, prevention of Wrong-route or -patient medication errors was achieved.

DISCUSSION

Wrong-route or -patient medication errors have been considered a serious issue in clinical settings (1,4,10,15). Although many efforts have been made to mitigate these issues, errors from unintentional human mistakes have remained difficult to fully resolve with the suggested strategies, which are heavily based on education or visual aid to provide reassurance regarding route and patient (2,15,18-21). In regards to human error, our system has an advantage over these other strategies, in that wrongful injections can be prevented and stopped at the source when the drug and route or patient mismatches. The adapters presented here can be prepared to possess a key and keyhole specific to the pair of medication and route or patient. In this way, a seamless connection and drug administration can be made only when the pair matches (Fig. 8). Under mismatching conditions, the medical staff can immediately recognize a possible error as the adapters cannot be smoothly connected. Even when injection is still attempted, the medication is leaked excessively (Fig. 8B) and cannot be delivered into the catheter, which would be connected to the vein of the patient.

To reduce the chances of a wrong-route medication error, a safety connector system had been introduced previously (29), which was designed to distinguish the difference between non-luer and luer connections, using a smaller size syringe tip, needle hub and stylet nose than those of conventional luer systems. Thus, when there is a mismatch, the clinician could physically recognize the misconnect and massive leakage of medication induced by an attempt of injection. Albeit similar to our approach in some ways, this system is not able to distinguish a specific pair of medication and route or patient among many possible combinations as only size is a measure of distinction.

In this work, we propose a RP technique for production of specific keys and keyholes for the syringe and catheter adapters, respectively. We envision that, just like the generation of a barcode, a key pattern specific to a pair of medication and route or patient can be generated at the time of hospital admittance. Given this, multiple distinct adapter pairs for many patients can be fabricated in a reasonable period of time (hours) with relatively low cost (Fig. 6) (23-25). At this state, any possible human errors can be minimized as the key and keyhole patterns can be generated electronically and this system can interwork together with the RP technique. However, the on-site production of the adapters may not be always necessary, as the hospital may already be equipped with many pre-made adapters, each possessing a distinct key and keyhole pattern. In this scenario, however, a strategy is needed to avoid the overlapped use of the same adapter pair among many different pairs of the medication and route or patient.

Our idea can be applied across many different clinical settings using syringes. The system can be specified for a patient to prevent the mistaken administration of a medicine to a different patient. Our system can also be used to differentiate the specific route of injection. For example, the system can be applied to an arterial line which is rarely used for injection of medicine. The syringe adapter can be used for enteral nutrients or enteral medicines. Therefore, we can prevent intravenous injection of enteral nutrients or enteral medicines into the venous system. An issue with the clinical application of our system may be added cost and the inconvenience of injection. However, we believe these issues pale in comparison to the overall improvement in patient safety and the use of adapter applied prefilled syringes.

In conclusion, we suggest a safety syringe system based on adapters that are equipped with key and keyhole patterns that are specifically assigned to the pair of drug and route or patient. The adapters can be connected to the syringe and catheter injection-port and thus, a seamless flow-path for injected liquid

 https://doi.org/10.3346/jkms.2017.32.12.1938

can be formed only when the key and keyhole patterns of the adapter pair match to form a secure connection. Like generating random numbers, thousands of matching patterns of key and keyhole can be generated with the strategy proposed herein. Therefore, we conclude that the safety injection system with the adapters herein has the potential to prevent wrong-route or -patient medication errors, and potentially save lives.

DISCLOSURE

The authors have no potential conflicts of interest to disclose.

AUTHOR CONTRIBUTION

Conceptualization: Cho YC, Lee SH, Cho YH, Choy YB. Data curation: Cho YC, Lee SH. Investigation: Cho YC, Lee SH. Writing - original draft: Cho YC, Lee SH. Writing - review & editing: Cho YC, Lee SH, Cho YH, Choy YB.

ORCID

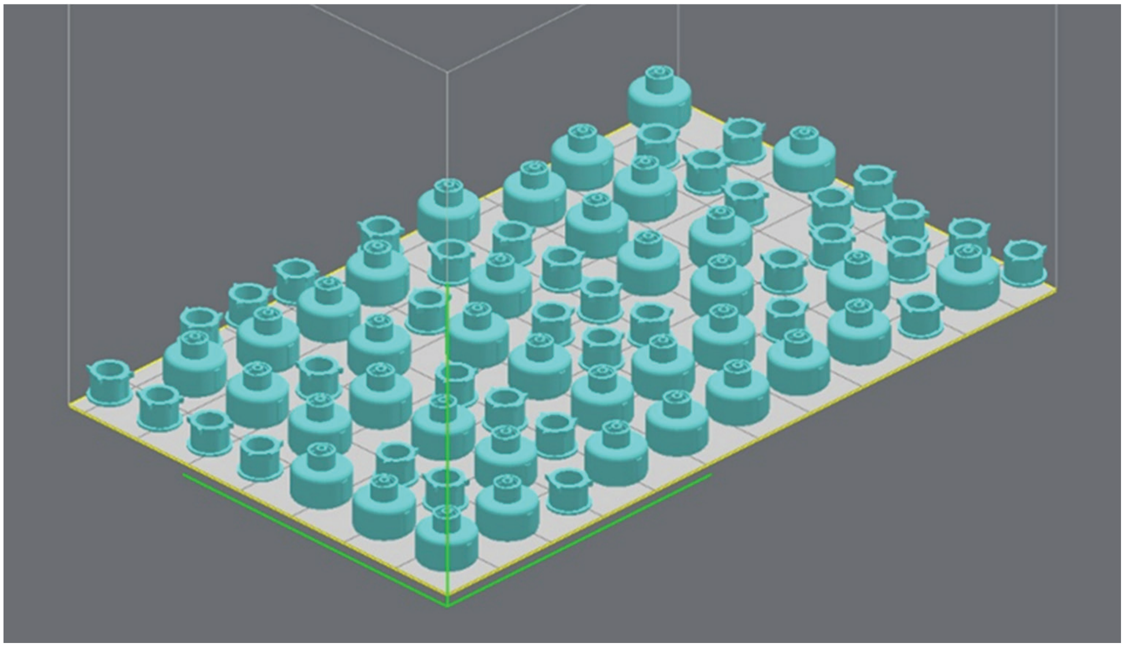
Yong Chan Cho https://orcid.org/0000-0001-7536-2098
Seung Ho Lee https://orcid.org/0000-0002-8383-0530
Yang Hyun Cho https://orcid.org/0000-0003-1685-3641
Young Bin Choy https://orcid.org/0000-0001-6300-9377

REFERENCES

1. Westbrook JI, Rob MI, Woods A, Parry D. Errors in the administration of intravenous medications in hospital and the role of correct procedures and nurse experience. *BMJ Qual Saf* 2011; 20: 1027-34.
2. Elliott M, Liu Y. The nine rights of medication administration: an overview. *Br J Nurs* 2010; 19: 300-5.
3. Pham JC, Story JL, Hicks RW, Shore AD, Morlock LL, Cheung DS, Kelen GD, Pronovost PJ. National study on the frequency, types, causes, and consequences of voluntarily reported emergency department medication errors. *J Emerg Med* 2011; 40: 485-92.
4. Teixeira TC, de Cassiani SH. Root cause analysis: evaluation of medication errors at a university hospital. *Rev Esc Enferm USP* 2010; 44: 139-46.
5. Cho WS. A study on the types and causes of medication errors and related drugs-by analyzing AJNs medication error 73 cases. *J Korea Community Health Nurs Acad Soc* 2002; 16: 176-89.
6. Fathi A, Hajizadeh M, Moradi K, Zandian H, Dezhkameh M, Kazemzadeh S, Rezaei S. Medication errors among nurses in teaching hospitals in the west of Iran: what we need to know about prevalence, types, and barriers to reporting. *Epidemiol Health* 2017; 39: e2017022.
7. Phillips J, Beam S, Brinker A, Holquist C, Honig P, Lee LY, Pamer C. Retrospective analysis of mortalities associated with medication errors. *Am J Health Syst Pharm* 2001; 58: 1835-41.
8. Kaushal R, Bates DW, Landrigan C, McKenna KJ, Clapp MD, Federico F, Goldmann DA. Medication errors and adverse drug events in pediatric inpatients. *JAMA* 2001; 285: 2114-20.
9. Prot S, Fontan JE, Alberti C, Bourdon O, Farnoux C, Macher MA, Foureau A, Faye A, Beaufils F, Gottot S, et al. Drug administration errors and their determinants in pediatric in-patients. *Int J Qual Health Care* 2005; 17: 381-9.
10. Grissinger M. Reducing the risk of deadly mixups with epidural and intravenous drugs. *P T* 2012; 37: 432, 434.
11. Linden JV, Wagner K, Voytovich AE, Sheehan J. Transfusion errors in New York State: an analysis of 10 years' experience. *Transfusion* 2000; 40: 1207-13.
12. National Health Service (GB). Never Events List 2015/16. London, NHS England, 2015.
13. Pongudom S, Chinthammitr Y. Inadvertent intrathecal vincristine administration: report of a fatal case despite cerebrospinal fluid lavage and a review of the literature. *J Med Assoc Thai* 2011; 94 Suppl 1: S258-63.
14. Reddy GK, Brown B, Nanda A. Fatal consequences of a simple mistake: how can a patient be saved from inadvertent intrathecal vincristine? *Clin Neurol Neurosurg* 2011; 113: 68-71.
15. Garrouste-Orgeas M, Philippart F, Bruel C, Max A, Lau N, Misset B. Overview of medical errors and adverse events. *Ann Intensive Care* 2012; 2: 2.
16. Kim M, Jeong S, Choi E, Ha H, Lee HY. Death after accidental injection of tranexamic acid during spinal anesthesia. *Korean J Leg Med* 2009; 33: 139-42.
17. Glavin RJ. Drug errors: consequences, mechanisms, and avoidance. *Br J Anaesth* 2010; 105: 76-82.
18. Yang A, Grissinger M. Wrong-patient medication errors: an analysis of event reports in Pennsylvania and strategies for prevention. *Pa Patient Saf Advis* 2013; 10: 41-9.
19. Bauters T, De Porre J, Janssens N, Van de Velde V, Verlooy J, Dhooge C, Robays H. Prevention of wrong route errors in a pediatric hemato-oncology ward. *Pharm World Sci* 2009; 31: 522-4.
20. Koppel R, Wetterneck T, Telles JL, Karsh BT. Workarounds to barcode medication administration systems: their occurrences, causes, and threats to patient safety. *J Am Med Inform Assoc* 2008; 15: 408-23.
21. Henneman PL, Marquard JL, Fisher DL, Bleil J, Walsh B, Henneman JP, Blank FS, Higgins AM, Nathanson BH, Henneman EA. Bar-code verification: reducing but not eliminating medication errors. *J Nurs Adm* 2012; 42: 562-6.
22. Choi JS, Kim D. Technical considerations for successful implementation of a barcode-based medication system in hospital. *J Korean Soc Med Inform* 2009; 15: 303-12.
23. Choonara YE, du Toit LC, Kumar P, Kondiah PP, Pillay V. 3D-printing and the effect on medical costs: a new era? *Expert Rev Pharmacoecon Outcomes Res* 2016; 16: 23-32.
24. Ihl C, Piller F. 3D printing as driver of localized manufacturing: expected benefits from producer and consumer perspectives. In: Ferdinand JP, Petschow U, Dickel S, editors. The Decentralized and Networked Future of Value Creation. Cham, Springer, 2016, p179-204.
25. Wong KV, Hernandez A. A review of additive manufacturing. *ISRN Mech Eng* 2012; 2012: 208760.
26. Sastri VR. Plastics in Medical Devices: Properties, Requirements, and Applications. Amsterdam, Elsevier/William Andrew, 2014.
27. United States Pharmacopeial Convention. United States Pharmacopeia. 23 - National Formulary 18. Rockville, MD, United States Pharmacopeial Convention, 1994.
28. Macdonald NP, Zhu F, Hall CJ, Reboud J, Crosier PS, Patton EE, Wlodkowic

D, Cooper JM. Assessment of biocompatibility of 3D printed photopolymers using zebrafish embryo toxicity assays. *Lab Chip* 2016; 16: 291-7.
29. Onia R, Wu Y, Parvu V, Eshun-Wilson I, Kassler-Taub K. Simulated evaluation of a non-Luer safety connector system for use in neuraxial procedures. *Br J Anaesth* 2012; 108: 134-9.

 https://doi.org/10.3346/jkms.2017.32.12.1938



Supplementary Fig. 1. Multiple 3D models of the distinct pairs of the adapters integrated in a single file.