Automated synthesis of radiopharmaceuticals for PET: an apparatus for [1-11C]labelled aldoses

Shintaro Nishimura, Kazuyoshi Yajima, Norihiro Harada, Yasuhiro Ogawa and Nobuyoshi Hayashi
Institute for Biofunctional Research, c/o National Cardiovascular Center, 7-1-5-Chome, Fujishiro-Dai, Suita City, Osaka 565, Japan

This paper describes an instrumentation system for positron emission tomography (PET). A variety of [1-11C]labelled aldoses, such as [1-11C]-d-glucose, and galactose by a modification of the Kiliani-Fischer method have been produced. The instrumentation is fully automatic and consists of a synthesis system and a control system. The synthesis system has the following functions: supplying reagents; performing reactions; purifying 11C labelled aldose; and preparing an injectable solution of 11C labelled aldose. These operations are performed by the control system in a remote control room. In a preliminary, hot experiment an injectable solution of [1-11C]-d-glucose was obtained. In addition, the operator is exposed to minimal radiation. The radioactivity of [1-11C]-D-glucose was 47 MBq, and the preparation time was 49 min.

Method

Development of a rapid synthetic method

Micro-scale synthetic study of aldoses was performed using a mock-up apparatus and cold experiments. The focus was on a modification of the Kiliani-Fischer method. Cyanohydrin formation with sodium cyanide and 2,3:4,5-di-O-isopropylidene-D-arabinose was investigated, and the optimum reaction conditions for preparing 3,4:5,6-di-O-isopropylidene-D-glucononitrile or mannononitrile by HPLC analysis were determined. Each aldononitrile was then converted to d-glucose or mannose by reductive hydrolysis with Raney nickel. In a similar manner, rapid synthetic methods for other aldoses were also investigated.

Construction of automated instrumentation

The automated instrument was built for the synthetic method. To minimize the operator's exposure to radiation, the hardware was designed to produce an injectable solution through a remote control. The apparatus was designed for laboratory use and for ease of improvement of the hardware and software. The software was programmed with Hyakuninriki (Asahi Electronics Co. Ltd, Japan) which operates under MS-DOS.

Hot experiment

After examining the synthesis of the aldoses in the cold test, an attempt was made to produce an injectable solution of [1-11C]-d-glucose from H11CN gas, which is prepared with a cyclotron and a H11CN gas generator—see figure 1. The production of 11C was accomplished by the nuclear reaction of accelerated protons with high pressurized 14N2 gas. This reaction was performed with a cyclotron and a target chamber. The picomole quantities of 11C undergo rapid oxidation to 11CO2 in the target chamber. The 11CO2 gas was then transferred to the H11CN gas generator and converted to d-glucose. Using these synthetic methods, several groups [7, 8] have developed remote or automated instruments for preparing [1-11C]-d-glucose. However, the majority of these instruments were not fully automatic and were not very flexible. This paper describes a new method for preparing optical isomers by changing the reaction conditions and a new instrument set up which is fully automatic and can synthesize other [1-11C]labelled aldoses.
S. Nishimura et al. Automated synthesis of radiopharmaceuticals for PET

Cyclotron Room

- Cyclotron
- Accelerated proton
- Target Chamber

Radiation Shielded Room

- Apparatus for [\(^{11}\)C]Aldoses
- \(^{11}\)CO\(_2\)
- H\(^{11}\)CN
- Eq.1
- Eq.2
- HPLC
- RIDC

PET Camera Room

- PET Camera

Local Area Network

Remote Controlling Room

- PC1
- PC2
- PC3
- PC4
- DP
- WS

Figure 1. Diagram of the production system for \([^{11}\text{C}]\)labelled aldoses. PC1 = personal computer (PC-9801RA, NEC) for controlling a cyclotron (HM-18, SHI), PC2 = personal computer (PC-9801FA, NEC) for controlling Eq. 1, PC3 = personal computer (PC-9801BX, NEC) for controlling Eq. 2, PC4 = personal computer (PC-9821Ap, NEC) for controlling the apparatus, DP = data processor (C-R4AX, Shimadzu), Eq. 1 = \(^{11}\text{CO}_2\) gas concentration equipment (AMCT01, NKK Corp.), Eq. 2 = \(^{11}\text{CN}\) gas generator (AMMC01, NKK Corp.), RIDC = radioisotope dose calibrator, WS = work station (SPARK station 10, SUN Microsystems).

H\(^{11}\text{CN}\) gas as shown below:

$$\begin{align*}
^{14}\text{N(p,\alpha)}^{11}\text{C} & \rightarrow ^{11}\text{CO}_2 \\
^{11}\text{CO}_2 & \rightarrow ^{11}\text{CH}_4 \\
\text{NH}_3, \text{Pt} & \rightarrow ^{11}\text{CN}
\end{align*}$$

Using the H\(^{11}\text{CN}\) gas as the starting material, the automated synthesis of \([^{11}\text{C}]\)-d-glucose was attempted. These operations were performed with four personal computers, and could be monitored with CCD video cameras in the remote controlling room. The product was analysed with a radioisotope dose calibrator and a HPLC system by remote monitoring and controlling.

Results and discussion

Chemistry

In order to investigate the possibility of selectively synthesizing either isomer by changing reaction conditions, reaction rate and the stereoselectivity of cyanohydrin formation was examined. As a typical example, the reaction of compound 1 with one equivalent of sodium cyanide in a mixture of organic solvent and alkali buffer was chosen:

1. Using the H\(^{11}\text{CN}\) gas as the starting material, the automated synthesis of \([^{11}\text{C}]\)-d-glucose was attempted. These operations were performed with four personal computers, and could be monitored with CCD video cameras in the remote controlling room. The product was analysed with a radioisotope dose calibrator and a HPLC system by remote monitoring and controlling.

2. The yields of the cyanohydrins, glucononitrile 2 and mannononitrile 3, were measured using HPLC. The total yield curve producing 2 and 3 versus reaction time is shown in figure 2. The initial reaction rate calculated from the summation yield of 2 and 3, depended upon the organic solvent. However, the total yield curves appeared to level off within 5 min. Interestingly, the formation ratio of 2 to 3 was found to be greatly dependent on the organic solvent and the pH of the buffer—figure 3.

These results can be divided into three groups. First is the glucononitrile 2 selective group, in which a mixture of toluene and alkali buffer was used as the reaction solvent. In these cases, the formation of 2/3 increased with the reaction time and the pH value of the buffer, and levelled off after 5 min. Second is the non-selective group,
in which a mixture of ethyl acetate or diisopropyl ether and alkali buffer was used. Last is the mannnononitrile 3 selective group, in which a mixture of ethanol and alkali buffer was used. The formation ratio reached the steady state after 2 min. It seems that the increasing ratio with time is caused by equilibrium reaction between 2 and 3, and that the formation ratio of 2/3 relates to the polarity of the organic solvent.

In addition, the toluene-buffer condition for preparing 2, which is the precursor of p-glucose, was examined. Figure 3 shows that the stereoselectivity of the cyanohydrin formation depends on the pH. Figure 4 shows the yield curves of 2 when the pH varied from 8.3 to 11.5, but the reaction rate tended to decrease at high pH such as pH 11.5. Thus, the optimum pH was found to be 10.8 in figure 4. To obtain a better understanding of the reaction mechanism, the dissociation rates of 2 and 3 were measured. After cyanohydrins 2 and 3 were isolated by silica gel chromatography, each sample (10 μmol) was added to a mixture of toluene (50 μl) and aqueous pH 10.8 buffer (1 M Na₂CO₃–1 M HCl, 50 μl). Each mixture was stirred at room temperature and analysed by HPLC as shown in figure 5. In both cases, the ratios of 2/3 varied with reaction time and after 5 min the ratios stabilized to 2:1:1. From these results, it is considered that the stereoselectivity of the cyanohydrin formation is not a result of cyanide attack on aldehyde 1, but, rather, it is due to an equilibrium reaction between the products 2 and 3. For the carbon-11 labelling, it was favourable that the equilibrium reaction proceeds rapidly. This method is practical and not moisture sensitive, so it is possible to apply to a microsynthesis of aldoses by combining it with a reductive hydrolysis step. Thus, a one-pot synthesis of p-glucose and mannose was as shown below:

\[
\text{CHO} \quad \text{NaCN} \quad \text{Raney Ni} \quad \text{HO}_2 \quad \text{HO} \quad \text{HO} \quad \text{HO} \\
\text{toluene} \quad \text{pH} 10.8 \text{ Buffer} \quad \text{R.t., 10 min} \quad \text{OH} \quad \text{OH} \quad \text{OH} \quad \text{HO}_2 \quad \text{OH} \\
\text{1 M Na}_2\text{CO}_3{\text{1 M HCl, 50 μl}} \\
\text{p-Glucose} \quad \text{3} \quad \text{Mannose}
\]
to give them in 23.0% and 13.5%, respectively. The one-pot reaction was performed within 15 min. Furthermore, we synthesized D-galactose (28.1%) and D-talose (11.9%) using a similar method from 2,3:4,5-O-isopropylidene-D-lyxose (4) [12]:

![Chemical reaction](image)

Automated apparatus for [1-11C]labelled aldoses

**General concept for the hardware**

The automated apparatus consists of the synthesis system and the controlling system. The synthesis system, an auto-manual switch box, and an interface are placed in a radiation shielded room. As these are removable, it is convenient for the cold experiment to be performed elsewhere and to facilitate the maintenance for the apparatus. The computer and its accessories are placed in the remote control room. The general appearance is shown in figures 6 and 7. The synthesis system consists of a series of units, which have the following functions: supplying reagents; performing reactions; purifying [1-11C]labelled aldose; and preparing an injectable solution of [1-11C]labelled aldose. These operations are performed by the controlling system and can be performed manually through the auto-manual switch box, which is useful in the case of the investigation with the cold experiment and the maintenance of the apparatus. As the solenoid valves and other devices of the reagents' supply unit and reaction unit were installed on the punched metal board, it is easy to modify the hardware.

**Synthesis system**

**Reagent and wash solvent supply unit**

The reagent supply unit [13] has eight reservoirs (12-19) in figure 8) for liquid reagents and solvents. Each reagent and solvent in the reservoirs is under nitrogen atmosphere, and can be transferred to the reaction flasks in two steps. First, the liquid is allowed to flow from the reservoir into a volumetric tube (0.5 ml) by nitrogen gas pressure. When the tube is full and the photosensor (45-52 in figure 8) is activated, the contents of the volumetric tube are emptied into the reaction flask by nitrogen gas pressure. The same volume of liquid may be repeatedly measured and added to the reaction flask. These operations are performed with three-way solenoid valves, photo-

---

**Figure 6. General view of the remote control room.**
sensors and nitrogen gas pressure. In this system, even moisture or air sensitive liquids can be stored in the reservoirs and transferred to the reaction flasks. After a synthetic run, all of the flow lines can be washed and dried by passing wash solvents which are stored in tanks (10 and 11 in figure 8), and then nitrogen gas through them.

**Reaction unit**

The reaction unit has two reaction flasks (20 and 21 in figure 8). Reaction flask 1 is used for the hydrocyanation of a precursor with NaCN and flask 2 is used for the reductive hydrolysis reaction. Both flasks are about 2 ml in volume and have jackets through which heating/cooling fluid is circulated with circulator 1 and 2 (24 and 25 in figure 8). The reaction temperature is maintained at the desired setting by the circulators. The mixing of the reaction mixture in the flasks are accomplished by nitrogen gas bubbling. The bubbling rate can be controlled with two mass flow controllers 1 and 2 (34 and 35 in figure 8). A reaction mixture in flask 1 can be transferred to flask 2 by using nitrogen gas pressure. The reaction mixture in flask 2 can be filtered with a glass filter, which is at the bottom of flask 2, and the filtrate can be transferred to the purification unit by using reduced pressure.

**Purification unit**

The purification unit consists of three devices: an ion exchange resin column (29 in figure 8), an evaporating device, and a preparative HPLC device. The filtrate from
flask 2 is desalted with the resin column and transferred to flask 3 for evaporation. Flask 3 also has a jacket through which heating fluid is circulated with circulator 3 (26 in figure 8), and is about 10 ml in volume. The mixing process in flask 3 is performed with the magnetic stirrer 1 (36 in figure 8). The evaporating process is carried out with a vacuum device (27 and 28 in figure 8). The concentrated mixture is then transferred to the auto-injection device through the bubble trap (42 in figure 8) with the roller pump 1 (40 in figure 8). An objective compound is isolated from the HPLC column (5 in figure 8) and detected with the refractive index and radiation detector (7 and 8 in figure 8). The eluate containing the objective compound is injected into the flask 4 (23 in figure 8).

**Pharmaceutical preparation unit**

The pharmaceutical preparation unit has three functions: adjusting the pH of the radiopharmaceutical solution; diluting with saline; and filtration with the filter 3 (56 in figure 8). The aqueous solution of the radiopharmaceutical in flask 4 is neutralized with a dilute acid or alkali solution from the reagent's supply unit. Flask 4 is equipped with the pH sensor (43 in figure 8), the level sensor (44 in figure 8), and the magnetic stirrer 2 (37 in figure 8). The radiopharmaceutical solution in flask 4 is filtered with the membrane filter and roller pump 2 (41 in figure 8). In the way, the ¹¹C-labelled compound is available in ready-to-use form for the PET study.

**Control**

**Computer and software**

The instrumentation is controlled with a personal computer (PC-9821Ap, NEC), which is linked with the other computers and LAN (Local Area Network) as shown in figure 1. An OPTMUX (Opto 22, USA) interface unit is used. The computer software was developed by using Hyakuninriki. The program consists of four processes as follows; hydrocyanation process; reductive hydrolysis process; purification process; and pharmaceutical preparation process. A flowchart of these processes is shown in figure 9.

The hydrocyanation process contains subroutines from ‘Add NaCN soln.’ to ‘Hydrocyanation in F1’. The reductive hydrolysis process contains subroutines of ‘Add HCl/HCOOH’ and ‘Reductive hydrolysis in F2’. The purification process contains subroutine from ‘Desalt’ to ‘HPLC’, and the pharmaceutical preparation process contains subroutines from ‘pH adjustment in F4’ to ‘Volume adjustment in F4’. The reaction processes are controlled by a time sequential method, and the injection process in HPLC is performed by sequential control using the signal of the photosensor. The processes of pH and volume adjustments are controlled by a closed-loop method.

The objective compound is automatically isolated by the following method. An HPLC chart of the reaction mixture in the case of the preparation for n-glucose is shown in

---

**Figure 9. Flowchart of the total operation. F1–4 = Flask 1–4.**
Automated synthesis of $[1-{ }^{11} C]$-D-glucose

The instrumentation is able to produce a series of $[1-{ }^{11} C]$-labelled aldoses; among these, $[1-{ }^{11} C]$-D-glucose is one of the most popular compounds for PET study. Therefore, an attempt was made to make an injectable solution of $[1-{ }^{11} C]$-D-glucose.

**Diagnosis check of the apparatus**

For radiation protection, a leak test on flasks 1 and 2 and their tube lines was performed by closing all outlets, opening them to the nitrogen gas flow line and monitoring the mass flow controllers. If zero flow could not be observed, the leak point was searched for and repaired until zero flow was established.

**Setting for a synthesis of $[1-{ }^{11} C]$-D-glucose**

The HPLC system turned on, then the fluid of the circulators warmed up to the desired temperature (circulator 1: 25°C, circulator 2: 105°C, circulator 3: 80°C).
S. Nishimura et al. Automated synthesis of radiopharmaceuticals for PET

24–26 in figure 8). The cold trap (27 in figure 8) for the vacuum pump had cooled to −50°C. The nitrogen gas regulator (31 in figure 8) was adjusted to 0.2–0.3 kg/cm².

The reservoirs (12–19 in figure 8) of the apparatus were filled as follows: reservoir 1 (a mixture solution of NaCN (10 mg, as a carrier) and pH 10.8 buffer (1 M Na₂CO₃–1 M HCl, 10 ml)), reservoir 2 (a solution of compound 1 [46 mg] in toluene, 10 ml), reservoir 3 (toluene, 10 ml for washing solvent), reservoir 4 (a mixture of imidazole (40 mg), 4 M HCl (0.5 ml) and formic acid (0.5 ml)), reservoir 5 (distilled water, 10 ml for washing solvent), reservoir 6 (0.01 M HCl, 10 ml), reservoir 7 (0.01 M NaHCO₃, 10 ml), reservoir 8 (saline, 10 ml). The wash solvent tanks (10 and 11 in figure 8) were filled as follows: tank 1 (distilled water, 1000 ml), tank 2 (methanol, 1000 ml). Raney nickel (40 mg) was added to reaction flask 2 (21 in figure 8).

**Synthesis of H¹¹CN**

The production of H¹¹CN was accomplished by an on-line synthesis according to Iwata’s method [11]. Production of H¹¹CO₂ was accomplished through ¹⁴N(p, p')¹¹C reaction by proton bombardment (18 MeV, 15 µA) of 14 karat/km². N₂ gas target was used with a cyclotron-target system (CYPRIS HM-18, Sumitomo Heavy Industries Co. Ltd). The ¹¹CO₂ gas in the target chamber was transferred to ¹¹CO₂ gas concentration equipment (AMCT 01, NKK Corp.) and then the concentrated ¹¹CO₂ gas was transferred to an H¹¹CN gas generator (AMHC 01, NKK Corp.) using He gas (flow rate: 100 ml/min) as a carrier gas, and hydrogenated (flow rate of H₂ gas: 10 ml/min) to give ¹¹CH₄ gas at 200°C in the presence of silica-gel supported Ru catalyst. The reaction of ¹¹CH₄ gas with NH₃ gas (flow rate: 5 ml/min) at 850°C in the presence of Pt catalyst gave off H¹¹CN gas, which was passed through a P₂O₅ (5-0 g) column to remove excess NH₃ gas, and then 16.9 GBq (at the end of bombardment) of H¹¹CN gas was transferred to the automated apparatus for [¹-¹¹C]-labelled aldoses.

**Hydrocyanation of compound 1**

Nitrogen gas flow rates of the mass flow controller 1 and 2 were set to zero. The outlet of circulator 2 was opened by switching valve 50. The mixture in flask 2 was mixed with nitrogen gas from mass flow controller 2 (nitrogen gas flow line: 30–35–V6-bottom of the flask 2) at a flow rate of 17.5 ml/min. The mixture was refluxed for 5 min. The waste gas was exhausted through valve 7 to the gas waste line. When the reaction was finished, the gas flow rate of the mass flow controller 2 was set to zero and valves 49 and 50 were closed to stop circulation.

**Reducive hydrolysis of [¹-¹¹C]aldononitrile**

A solution of formic acid, 4 M HCl, and imidazole (0.5 ml) from reservoir 4, was added to the mixture of the cyanohydrins and Raney nickel in flask 2. The outlet of circulator 2 was opened by switching valve 50. The mixture in flask 2 was mixed with nitrogen gas from mass flow controller 2 (nitrogen gas flow line: 30–35–V6-bottom of the flask 2) at a flow rate of 17.5 ml/min. The mixture was refluxed for 5 min. The waste gas was exhausted through valve 7 to the gas waste line. When the reaction was finished, the gas flow rate of the mass flow controller 2 was set to zero and valves 49 and 50 were closed to stop circulation.

**Purification and pharmaceutical preparation of [¹-¹¹C]-D-glucose**

The power switch of the vacuum pump and the magnetic stirrer 1 under flask 3 were turned on. The outlet of circulator 3 was opened by switching valve 51. When valves 6 and 16 were switched, the mixture was filtered with a glass filter fitted at the bottom of flask 2, the filtrate was passed through valve 6 and the ion exchange resin column (IRN-150L, 4.6 mm x 30 cm, Organo Co. Ltd) to flask 3. Evaporation of the contents of flask 3 was then performed by switching valve 50. While the evaporation was running, washing solvent (6.5 ml of water, 0.5 ml x 13 portions) from reservoir 5 was added to flask 2 (flow line: 16–V21–V9–V8-top of flask 2) in a similar manner, and then transferred to flask 3 through valve 6 and the column in the same manner. When the evaporation was finished, the outlet of circulator 3 was closed by switching valve 51, and in order to break the vacuum line valves 10, 16, and 56 were switched and the power switch of the vacuum pump was turned off. The residue in flask 3 was dissolved in 0.5 ml water delivered from reservoir 5 in a similar manner (flow line: 16–V21–V9–V11-flask 3). After dissolving the residue, magnetic stirring was stopped, the aqueous solution was injected to the HPLC system as follows: valves 10 and 11 were switched, the aqueous solution containing air bubbles was delivered to the bubble trap via valve 58 with the roller pump 1, the debubbled solution in the bubble trap was sent to the sample loop via photosensor 9 and the rotary six-way valve, when the end of the solution line was detected by the photosensor 9, the rotary six-way valve was switched and the solution in the sample loop was loaded to the HPLC column.
The HPLC separation conditions were as follows: column: Bio-Rad Aminex HPX-87P (7.8 mm x 30 cm, 9 µm), mobile phase: water, flow rate: 0.6 ml/min, temperature: 85°C, retention time of D-glucose: 13.4 min. When the eluate containing [1-11C]-D-glucose was detected in the refractive index detector (RI-71, Shodex Co. Ltd) and the radiation detector (TCS-R81-3454, Aloka Co. Ltd), valve 12 was switched and the eluate was transferred to flask 4. The magnetic stirrer was switched on and the pH value of the eluate in flask 4 was measured with the pH sensor. As the pH value was in the range of 6.5 to 7.5, the addition of the acid in reservoir 6 or the alkali in reservoir 7 was not performed. Thus the solution was diluted with the saline in reservoir 8. The saline was added to flask 4 repeatedly until the level sensor was activated which was set to a volume of 10 ml. Finally, the injectable solution of [1-11C]-D-glucose was obtained by filtration with roller pump 2 and the membrane filter 3. The total synthesis time was 49 min. The product was analysed by remote monitoring and operating and the analysis data were found to be as follows: chemical yield 2.0% from NaCN, radiochemical yield 1.3% from H11CN, radioactivity of [1-11C]-D-glucose 47 MBq, chemical purity: >96%, radiochemical purity >95%.

Conclusion

A rapid synthesis of aldono nitrile compounds using an equilibrium reaction has been developed and the results show the feasibility of synthesis of either 2R or 2S aldoses under simple reaction conditions. On the basis of these investigations, an automated synthesis instrument was built which is capable of producing a wide variety of [1-11C]labelled aldoses in a ready-to-inject form. As the instrument consists of a series of units and can be improved, it may be appropriate for laboratory use.

A preliminary, hot experiment using the instrument was successful and an injectable solution of [1-11C]-D-glucose was obtained automatically. The difference in yield between the cold experiment and the hot experiment could be caused by the absorption in the flasks and columns. The authors are now working on the optimization of the operation conditions and the synthesis of the other labelled aldoses.

Experimental

Materials and reagents

Raney nickel was purchased from Nakarai Tesque, Inc. The other reagents and organic solvents were purchased from Wako Pure Chemical Industries, Ltd. All solvents were distilled and filtered with a membrane filter before use.

Analysis

The melting-point of compound 2 is measured with a Yanagimoto micro melting-point apparatus without correction. NMR were recorded using Varian Instruments’ GEM-300 spectrometer. Chemical shifts (δ) were recorded in ppm from tetramethylsilane (in CDCl3 and C6D6) as an internal standard. HPLC analysis was performed with a Shimadzu LC-9A pump, a Shodex refractive index detector RISE-61, an Aloka positron detector TCS-R81-3454 and three separate analytic systems were used:

1. Analysis of aldono nitrile 2 and 3:
   Column: Waters radialpak C-18 (8 mm x 10 cm, 5 µm).
   Mobile phase: acetonitrile:0.003 M KH2PO4 = 2:3.
   Flow rate: 1.5 ml/min.
   Temperature: 85°C.
   Retention time: compound 2 (12.38 min), compound 3 (11.47 min).

2. Analysis of aldoses:
   Column: Bio-Rad Aminex HPX-87P (7.8 mm x 30 cm, 9 µm).
   Mobile phase: water.
   Flow rate: 0.6 ml/min.
   Temperature: 85°C.
   Retention time: D-glucose (13.40 min), D-mannose (17.20 min), D-arabinose (16.30 min), D-galactose (14.53 min), D-talose (31.19 min), D-lyxose (17.38 min).

3. Analysis of aldoses:
   Column: Shodex Ionpak KS-801 (8 mm x 30 cm).
   Mobile phase: water.
   Flow rate: 1.0 ml/min.
   Temperature: 80°C.
   Retention time: D-glucose (8.20 min), D-mannose (8.70 min), D-arabinose (9.30 min).

The analysis of [1-11C]-D-glucose was performed by remote control. The HPLC analysis was accomplished using a Shimadzu LC-9A pump, a Shodex refractive index detector RISE-61, an Aloka positron detector TCS-R81-3454, a hand made auto sampler, and a Shimadzu C-R4AX two-channel data processor. The radioactivity of the product was measured with a CAPINTEC CRC-712 dose calibrator.

Cold synthesis of aldose derivatives

Preparation of 3,4:5,6-di-O-isopropylidene-D-glucosonitrile 2 and 3,4:5,6-di-O-isopropylidene-D-mannosonitrile 3

To a solution of compound 1 [9] (450 mg, 1.95 mmol) in toluene (10 ml) was added a mixture of sodium cyanide (96 mg, 1.95 mmol) and pH 10-8 buffer (10 ml, 1 M Na2CO3-1 M HCl) at 25°C. The mixture was stirred at the same temperature for 10 min. The organic layer was separated, dried with anhydrous sodium sulphate, and evaporated in vacuo to give colourless oil. The residue was purified by silica-gel column chromatography (Wako, Wakogel C-200, 25 g, dichloromethane:diethyl ether = 40:1) to give compound 2 (218 mg, 43.5% as crystals) and compound 3 (118 mg, 23.5% as a colourless oil), respectively. Compound 2: melting point 82–84°C; 1H NMR (CD3OD) δ = 1.135 (3H, s, CH3) 1.286 (3H, s, CH3), 1.396 (3H, s, CH3), 1.419 (3H, s, CH3), 3.3672 (1H, m, J = 6 Hz and 9 Hz, H-5), 3.771 (1H, dd, J = 30 and 9 Hz, H-3), 3.878 (1H, dd, J = 60 and 9 Hz, H-3).
H-6a), 3.982 (1H, q, J = 9.1 Hz, H-6b), 4.178 (1H, t, J = 9.1 Hz, H-4), 4.461 (1H, d, J = 11.3 Hz, 1-OH), 4.633 (1H, dd, J = 3.0 and 11.3 Hz, H-2); 13C NMR (CD6) δ = 24.772 (CH3), 26.316 (CH3), 26.523 (CH3), 26.920 (CH3), 61.897 (C-2), 67.684 (C-6), 75.939 (C-5), 78.789 (C-4), 80.244 (C-3), 110.766 (isopropylidene, C), 118.445 (C-1). Compound 3: 1H NMR (CDCl3) δ = 1.355 (3H, s, CH3), 1.431 (3H, s, CH3), 1.441 (3H, s, CH3), 1.471 (3H, s, CH3), 3.763 (1H, dd, J = 7.9 and 8.5 Hz, H-4), 4.101 (1H, dd, J = 5.1 and 8.4 Hz, H-6a), 4.070 (1H, m, J = 5.1 and 7.9 Hz, H-3), 4.192 (1H, dd, J = 5.7 and 8.4 Hz, H-6b), 4.388 (1H, d, J = 5.1 Hz, H-2); 13C NMR (CDCl3) δ = 25.043 (CH3), 26.208 (CH3), 26.679 (CH3), 26.942 (CH3), 63.516 (C-2), 67.799 (C-6), 76.271 (C-5), 79.292 (C-4), 80.577 (C-3), 109.98 (isopropylidene, C), 117.496 (C-1).

One-pot synthesis of D-glucose and D-mannose
A mixture of sodium cyanide (5 mg, 0.1 mmol) and pH 10.8 buffer (0.5 ml, 1 M Na2CO3 - 1 M HCl) at 25°C was added to a solution of compound 1 (23 mg, 0.1 mmol) in toluene (0.5 ml). The mixture was stirred at the same temperature for 10 min. To the mixture was added a mixture of Raney nickel (40 mg), formic acid (0.25 ml), 4 M HCl (0.25 ml), and imidazole (20 mg). The mixture was heated at 105°C for 5 min, and then filtered. The filtrate was evaporated in vacuo to give a residue. The purification was performed by the HPLC system to give D-glucose (4.1 mg, 23.0%) and D-mannose (2.4 mg, 13.5%), respectively. These operations were carried out using the mock-up apparatus.

One-pot synthesis of D-galactose and D-talose
These compounds were prepared in a similar manner to that of D-glucose and D-mannose. The starting material, 2,3,4,5-di-O-isopropylidene-D-lyxose (4) can be derived by Lee's method [12]. In this way, D-galactose and D-talose were obtained in yields of 28.1% and 11.9%, respectively.

Acknowledgements
The authors wish to thank Dr Teruo Omae, President of the National Cardiovascular Center, for supporting this work, and to Drs Masadzumi Watanabe, Tohru Sugawara, and D. G. Cork at Takeda Chemical Industries Ltd for useful discussions.

References
1. Wolf, A. P. and Flower, J. S., in Positron Emission Tomography, Reivich, M. and Alavi, A. (Eds) (Alan R. Liss Inc., New York, 1985), 63.
2. Raichle, M. E., Larson, K. B., Phelps, M. E., Grubb, Jr., R. L. and Ter-Pogossian, M. M., American Journal of Physiology, 228 (1975), 1936.
3. Bergstrom, M., Collins, P. and Ehren, E., Computer Assisted Tomography, 7 (1983), 1062.
4. Shue, C.-Y. and Wolf, A. P., Journal of Labelled Compounds and Radiopharmaceuticals, 22 (1985), 171.
5. Schoeps, K.-O., Langerstrom, B., Stone-Elander, S. and Halldin, C., Applied Radiation and Isotopes, 42 (1991), 877.
6. Denge, C. S. and Welch, M. J., Journal of Labelled Compounds and Radiopharmaceuticals, 32 (1995), 574.
7. Links, J. M., Courter, J. H. and Krohn, K. A., Journal of Nuclear Medicine, 30 (1989), 928.
8. Stone-Elander, S., Halldin, C., Langerstrom, B., Blomqvist, G. and Widen, L., Applied Radiation and Isotopes, 43 (1992), 721.
9. Zimmer, H., Wittenburg, E. and Rembarz, G., Chemische Berichte, 92 (1959), 721.
10. Nishimura, S. and Hayashi, N., Chemistry Letters (Japan) (1991), 1815.
11. Iwata, R., Ido, T., Takahashi, H. and Iida, S., Applied Radiation and Isotopes, 38 (1987), 97.
12. Lee, A. W. M., Martin, V. S., Masamune, S., Sharpless, K. B. and Walker, F. J., Journal of American Chemical Society, 104 (1982), 3515.
13. Hayashi, N., Sugawara, T., Shintani, M. and Kato, S., Journal of Automatic Chemistry, 11 (1989), 212.