Selective Hydrogenation of Cyclic Imides to Diols and Amines and its Application in the Development of a Liquid Organic Hydrogen Carrier.

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1. General information

All experiments were carried out in M-BRAUN Unilab 1200/780 glovebox under inert atmosphere of purified nitrogen or using standard Schlenk techniques. Tetrahydrofuran (THF), toluene, benzene and \( n \)-pentane were refluxed over sodium/benzophenone, distilled under argon atmosphere, and stored over 4 Å molecular sieves (MS). Most of the chemicals used in the catalytic reactions were purified according to standard procedures (vacuum distillation).\(^1\) Deuterated solvents were degassed with argon and kept in the glovebox over 4 Å MS. Commercial potassium hydride and KO\(^{1}\)Bu were washed with dry pentane to afford white solid before use. Alcohols and amines were purchased from Strem, Sigma Aldrich or Alfa Aesar, and used as received. Phthalimides were synthesized from phthalic anhydride and primary amine according to Godt’s procedure for N-benzylphthalimide.\(^2\) Characterization data for phthalimides with variable N-substituents can be found in the literature:\(^2\)-\(^7\) 4-methoxybenzyl, 3-picolyl,\(^3\) phenyl, 4-methylbenzyl, 4-trifluoromethylbenzyl,\(^4\) 2-chlorobenzyl\(^5\) 4-fluorobenzyl,\(^6\) hexyl, and 4-chlorobenzyl.\(^7\) N-phenylmaleimide was purchased commercially. N-benzylmaleimide and N-benzylglutarimide were synthesized according to Patil’s method.\(^8\) Bis-cyclic imide was synthesized from isolated potassium succinimide\(^9\) and 1,2-dibromoethane, adapted from Lion’s procedure.\(^10\) N-hexyl succinimide was synthesized according to Schmitt’s procedure,\(^11\) other succinimides were synthesized according to Giray’s method.\(^12\) Characterization data for the succinimides can be found in our previous report.\(^13\) The ruthenium complexes \([\text{RuPNN}(\text{H})(\text{Cl})(\text{CO})]^{14}\) (1), \([\text{RuPNN}_{\text{bpy}}(\text{H})(\text{Cl})(\text{CO})]^{15}\) (2) and \([\text{Ru}^{\text{Bu}}\text{NNH}(\text{H})(\text{Cl})(\text{CO})]^{16}\) (3) were prepared according to the literature procedures described earlier.\(^1\)H NMR, \(^13\)C\({}^{1}\text{H}\) NMR, and \(^31\)P\({}^{1}\text{H}\) NMR spectra were recorded on a Bruker AMX-400 NMR spectrometer and reported in ppm (\(\delta\)). \(^1\)H NMR, \(^13\)C\({}^{1}\text{H}\) NMR, and \(^13\)C\({}^{1}\text{H}\)-DEPTQ NMR chemical shifts are referenced with respect to tetramethylsilane, while \(^31\)P\({}^{1}\text{H}\) NMR chemical shifts are reported referenced to an external 85% solution of phosphoric acid in D\(_2\)O. NMR spectroscopy abbreviations: b, broad; s, singlet; d, doublet; t, triplet; q, quartet.
m, multiplet. GC–MS was carried out on HP 6890 / 5973 (MS detector) instruments equipped with a 30 m column (Restek 5MS, 0.32 mm internal diameter) with a 5% phenylmethylsilicone coating (0.25 mm) and helium as carrier gas. IR spectrum was recorded on a Nicolet FTIR spectrophotometer. ESI-MS experiment was performed on Xevo G2-XS QTof instrument.

2. Preparation and characterization of [Ru(PPhNNH)(CO)(H)(Cl)] (4).

![Diagram of reaction](image)

A suspension of [Ru(PPh3)3(CO)(H)(Cl)] (953 mg, 1.0 mmol) in 15 mL of THF was added to N-((6-((di-phenylphosphanyl)methyl)pyridin-2-yl)methyl)-2-methylpropan-2-amine (PPhNNH, L) ligand (435 mg, 1.2 mmol) and the reaction mixture was stirred at 80 °C overnight (~16 h). It was then brought to room temperature and the solvent was concentrated to approximately half of the volume. Diethyl ether was added to precipitate the product. The precipitate was washed with ether to afford complex 4 as a yellowish solid in 82% yield (433 mg).

\[ ^{31}P\{^{1}H\} \text{NMR (162.06 MHz, DCM-}d^2, \text{298 K): } \delta \text{ 72.7 (s).} \]

\[ ^{1}H \text{NMR (400.35 MHz, DCM-}d^2, \text{298 K): } \delta \text{ -14.50 (d, } ^{2}J_{HP} = 24.5 \text{ Hz, 1H, Ru-H), 1.59 (s, 9H, (CH}_3)_2\text{CN), 4.27 to 4.44 (m, 4H, NH, PCHH, NCHH), 4.56 (m, 1H, PCHH), 7.34 (d, } ^{3}J_{HH} = 7.7 \text{ Hz, 1H, CH}_{pyri(5)}, \text{ 7.46 (m, 3H, PPh), 7.55 (m, 4H, PPh), 7.63 (m, 2H, PPh, CH}_{pyri(3)}, \text{ 7.81 (t, } ^{3}J_{HH} = 7.7 \text{ Hz, 1H, CH}_{pyri(4)}, \text{ 8.02 (m, 2H, PPh).} \]
$^{13}$C($^1$H) DEPT NMR (100.68 MHz, DCM-$d^2$, 298 K): δ 28.8 (s, (CH$_3$)$_3$CN), 44.2 (d, $^1$J$_{PC} = 25.5$ Hz, CH$_2$P), 55.3 (s, CH$_2$N), 55.6 (s, (CH$_3$)$_3$CN), 119.0 (s, CH$_{pyr1(5)}$), 121.2 (d, $^3$J$_{PC} = 10.2$ Hz, CH$_{pyr1(3)}$), 128.3 (t, $^2$J$_{PC} = 10.4$ Hz, PPh), 129.8 (bs, PPh), 130.4 (bs, PPh), 131.2 (d, $^1$J$_{PC} = 10.8$ Hz, PPh), 133.5 (d, $^1$J$_{PC} = 11.8$ Hz, PPh), 137.4 (s, CH$_{pyr1(4)}$), 139.7 (d, $^1$J$_{PC} = 49.3$ Hz, PPh), 158.7 (bd, $^4$J$_{PC} = 5.5$ Hz, CH$_{pyr1(6)}$), 159.6 (bs, CH$_{pyr1(2)}$), 229.9 (bd, $^2$J$_{PC} = 21.0$ Hz, Mn-CO), 207.6 (d, $^2$J$_{PC} = 18.0$ Hz, Ru-CO).

IR (NaCl pellet, cm$^{-1}$): 1940 (C=O stretching).

Figure S1. $^{31}$P($^1$H) NMR (162.06 MHz, DCM-$d^2$, 298 K) spectrum of complex 4.
Figure S2. $^1$H NMR (400.35 MHz, DCM-$d^2$, 298 K) spectrum of complex 4.
Figure S3. $^{13}$C($^1$H) DEPT NMR (100.68 MHz, DCM-$d_2$, 298 K) spectrum of complex 4.

Figure S4. FTIR spectrum of complex 4.
3. Hydrogenation of phthalimides

General procedure

\[
\text{RbuNNH complex (3, 0.01 mmol) and KO}^\text{Bu (0.03 mmol) were mixed in a vial to which 1 mL of THF was added resulting in a deep blue solution. In another vial 1 mmol of the phthalimide was weighed and dissolved in 1 mL THF. The deep blue catalytic solution was mixed with the phthalimide solution and transferred to an autoclave. The autoclave was pressurized with 20 bar of H}_2 \text{ and heated at 110 °C for 24 hours. The reaction mixture was then cooled down in an ice bath for 15 min before releasing the H}_2 \text{ pressure. Then 1 mmol of an internal standard (toluene) was added to the reaction mixture. The conversion of phthalimide and yield of amine were obtained by analyzing the reaction mixture by GC. After that, the THF solvent was evaporated and the resulting crude material was dissolved in CDCl}_3 \text{ to which 1 mmol of an internal standard (toluene or mesitylene) was added. The yield of 1,2-benzenedimethanol was determined by }^1\text{H NMR spectroscopy. The conversion of phthalimide and yield of amine were also confirmed by }^1\text{H NMR spectroscopy.}
Table S1. Optimization of the hydrogenation of phthalimides.

| Entry | Complex | KOTBu (mol%) | Cyclic imide conversion<sup>a</sup> | Yield of amine<sup>b</sup> | Yield of diolefin<sup>b</sup> |
|-------|---------|--------------|-------------------------------|----------------|---------------------|
| 1     | 1       | 1 mol%       | 67%                           | 65%            | 60%                 |
| 2     | 2       | 1 mol%       | 63%                           | 62%            | 55%                 |
| 3     | 3       | 1 mol%       | 84%                           | 80%            | 78%                 |
| 4     | 3       | 3 mol%       | 99%                           | 99%            | 96%                 |

<sup>a</sup> detected by <sup>1</sup>H NMR spectroscopy. <sup>b</sup> detected by GC.

Figure S5. <sup>1</sup>H NMR spectrum (400.35 MHz, CDCl<sub>3</sub>, 298 K) of the crude material (after removing the solvent) after the hydrogenation of N-benzylphthalimide using mesitylene as an internal standard.
4. General procedure for the hydrogenation of succinimides, maleimides and glutarimides

The RuP^Bu NNH complex (3, 0.005 mmol) and KO^Bu (0.015 mmol) were mixed in a vial to which 1 mL of 1,4-dioxane was added resulting a deep blue solution. In another vial 0.5 mmol of the imide was weighed and dissolved in 1 mL 1,4-dioxane. The deep blue catalytic solution was mixed with the imide solution and transferred to an autoclave. The autoclave was pressurized with 40 bar of H\textsubscript{2} and heated at 135 °C for 40 hours. The reaction mixture was then cooled down in an ice bath for 15 min before releasing H\textsubscript{2} pressure. Then 1 mmol of an internal standard (toluene) was added to the reaction mixture. The yield of amine was obtained by analyzing the reaction mixture by GC. After that, the dioxane solvent was evaporated and the resulting crude material was dissolved in CDCl\textsubscript{3} to which 0.5 mmol of an internal standard (mesitylene) was added. The conversion of imide and the corresponding yield of diol and amine were detected by the \textsuperscript{1}H NMR spectroscopy (Figures S6-S8).
Figure S6. $^1$H NMR spectrum (400.35 MHz, CDCl$_3$, 298 K) of the crude material (after removing solvent) in CDCl$_3$ after the hydrogenation of 4-fluoro-N-benzylsuccinimide (Table 2, entry 4) using mesitylene as an internal standard.
Figure S7. $^1$H NMR spectrum (400.35 MHz, CDCl$_3$, 298 K) of the crude material (after removing solvent) in CDCl$_3$ after the hydrogenation of N-benzylmaleimide (Table 2, entry 9) using mesitylene as an internal standard.

Figure S8. $^1$H NMR spectrum (400.35 MHz, CDCl$_3$, 298 K) of the crude material (after removing solvent) in CDCl$_3$ after the hydrogenation of N-benzylglutarimide (Table 2, entry 10) using mesitylene as an internal standard.
5. General procedure for the dehydrogenative coupling of 1,4-butanediol and ethylenediamine

![Chemical structure diagram]

Table S2. Optimization of the dehydrogenating coupling of 1,4-butanediol and ethylenediamine.

| Entry | cat | Base (mol%) | Solvent (mL) | temp (°C) | H₂ (mL) | Diol conversion | Product yield |
|-------|-----|-------------|--------------|-----------|---------|----------------|--------------|
| 1     | 1   | KOtBu (1 mol%) | Dioxane (2 mL) | 120      | 70 mL  | 95%            | Imide (55%) + lactone (20%) + oligoamide |
| 2     | 2   | KOtBu (1 mol%) | Dioxane (2 mL) | 120      | 62 mL  | 90%            | Imide (40%) + lactone (25%) + oligoamide |
| 3     | 3   | KOtBu (2 mol%) | Dioxane (2 mL) | 120      | 58 mL  | 99%            | Imide (34%) + lactone (30%) + oligoamide |
| 4     | 4   | KOtBu (2 mol%) | Dioxane (2 mL) | 120      | 82 mL  | 99%            | Imide (70%) + lactone (12%) + oligoamide |
| 5     | 4   | KOtBu (2 mol%) | Dioxane (1 mL) | 120      | 81 mL  | 99%            | Imide (63%) + lactone (24%) + oligoamide |
| 6     | 4   | KOtBu (2 mol%) | Dioxane (1 mL) | 135      | 82 mL  | 99%            | Imide (60%) + lactone (20%) + oligoamide |
| 7     | 4   | KH (2 mol%)   | Dioxane (2 mL) | 120      | 68 mL  | 99%            | Imide (58%) + lactone (27%) + oligoamide |
| 8     | 1   | KOtBu (1 mol%) | Tol (2 mL)    | 120      | 55 mL  | 88%            | Imide (40%) + lactone (20%) + oligoamide |
| 9     | 2   | KOtBu (1 mol%) | Tol (2 mL)    | 120      | 58 mL  | 89%            | Imide (44%) + lactone (19%) + oligoamide |
| 10    | 3   | KOtBu (2 mol%) | Tol (2 mL)    | 120      | 62 mL  | 96%            | Imide (48%) + lactone (22%) + oligoamide |
| 11    | 4   | KOtBu (2 mol%) | Tol (2 mL)    | 120      | 65 mL  | 99%            | Imide (53%) + lactone (20%) + oligoamide |
| 12    | 4   | KH (2 mol%)   | Tol (2 mL)    | 120      | 74 mL  | 99%            | Imide (65%) + lactone (15%) + oligoamide |

The ruthenium complex 3 (0.01 mmol) and base (0.02 mmol) were mixed in a vial to which 1 mL of 1,4-dioxane was added resulting in a deep blue solution. In another vial 1 mmol of 1,4-butanediol and 0.6 mmol of ethylenediamine were weighed to which 1 mL of 1,4-dioxane was added. The deep blue catalytic solution was mixed with the substrates and transferred to a 100 mL Young’s tube. The reaction mixture was heated at 120°C for 24 hours and then cooled down to room temperature and the amount of hydrogen gas was measured using the gas-burette method as used by us earlier.13 The conversion of the diol and diamine in the crude reaction mixture were determined by the ¹H NMR spectroscopy using toluene as an internal standard. The reaction mixture was then evaporated to remove the dioxane. The solid obtained was dissolved in excess CDCl₃ or CDCl₃/CHCl₃ mixture. 2 mmol of mesitylene as an internal standard was added to the reaction mixture. Yields of the products were determined by ¹H NMR spectroscopy as shown below in Figure S9. Oligoamides were characterized based on the NMR spectra reported for the analogous polymers prepared from diols and diamines and by the ESI-MS.18 Bis-succinimide was isolated by the crystallization from the concentrated dioxane.
solution of the product mixture at -20°C in approximately 60% yield in case of entry 4 (Table S2).

Note: The amount of hydrogen gas from the dehydrogenative coupling of 1,4-butanediol and ethylene diamine were approximately same (~80 mL, conditions: Table S2, entry 4) whether the reaction was performed in a 100 mL Youngs’ tube, closed system or a 50 mL open Schlenk tube, with collection of the hydrogen using a system previously used by us.19

Figure S9. $^1$H NMR spectrum (400.35 MHz, CDCl$_3$, 298 K) of the crude material in CDCl$_3$ after the dehydrogenative coupling of 1,4-butanediol and ethylenediamine using mesitylene as an internal standard (Table S2, entry 3). Signals corresponding to oligoamides are represented with asterisks *.
Figure S10. $^1$H NMR spectrum (400.35 MHz, CDCl$_3$, 298 K) of the isolated bis-succinimide.

Figure S11. $^{13}$C($^1$H) NMR (100.68 MHz, DCM-$d^2$, 298 K) spectrum of the isolated bis-succinimide.
Characterization of the oligoamides by mass spectrometry

ESI-MS of the reaction mixture obtained from the entry 4, Table S1 showed the presence of lactone (87.08, M+H⁺) and bis-cyclic imide (247.16, M+Na⁺) as observed by the ¹H NMR spectroscopy. Additionally, signals corresponding to oligoamides were observed at 143.22 (n = 1, M+H⁺), 285.26 (n = 2, M+H⁺) and 427.33 (n = 3, M+H⁺). Signals corresponding to the polymer fragmentation were observed at 229.20 (M₁+H⁺), 251.19 (M₁+Na⁺), 371.31 (M₂+H⁺) and 393.31 (M₂+Na⁺).

Figure S12. ESI-MS (positive mode) image in the mass range of 0 - 2000 m/z.
Figure S13. ESI-MS (positive mode) image in the mass range of 50 - 700 m/z.
6. General procedure for the hydrogenation of *bis*-cyclic imide

Table S3. Hydrogenation of *bis*-cyclic imide to 1,4-butanediol and ethylenediamine.

![Chemical structure](image)

| Entry | Catalyst | KOTBu (mol%) | cyclic imide conversion | diol yield | diamine yield |
|-------|----------|--------------|-------------------------|------------|---------------|
| 1     | 1        | 1 mol%       | 75%                     | 70%        | 75%           |
| 2     | 2        | 1 mol%       | 84%                     | 81%        | 80%           |
| 3     | 3        | 3 mol%       | 99%                     | 90%        | 92%           |
| 4     | 4        | 3 mol%       | 65%                     | 50%        | 65%           |

Conditions: *bis*-cyclic imide (0.5 mmol), complexes 1-4 (0.005 mmol), KOTBu (0.005-0.015 mmol), 1,4-dioxane (2 mL), 135°C, 24 h. Conversion of diol and yield of *bis*-cyclic imide are detected by $^1$H NMR spectroscopy using toluene as an internal standard.

Ruthenium complex (1-4, 0.005 mmol) and KOTBu (0.005 - 0.015 mmol, as described in the table above) were mixed in a vial to which 1 mL of 1,4-dioxane was added resulting a deep blue solution. In another vial 0.5 mmol of *bis*-cyclic imide was weighed and dissolved in 1 mL 1,4-dioxane. The catalytic solution was mixed with the *bis*-cyclic imide solution and transferred to an autoclave. The autoclave was pressurized with 40 bar of H$_2$ and heated at 135 °C for 40 hours. The reaction mixture was then cooled down in an ice bath for 15 min before releasing the H$_2$ pressure. 1mmol of mesitylene was then added as an internal standard to the reaction mixture. The conversion of *bis*-cyclic imide and the corresponding yield of 1,4-butanediol and ethylenediamine were detected by the $^1$H NMR spectroscopy (Figures S14).
Figure S14. $^1$H NMR spectrum (400.35 MHz, CDCl$_3$, 298 K) of the crude material in CDCl$_3$ after the hydrogenation of bis-succinimide using mesitylene as an internal standard.

7. Hydrogenation of the discharged material obtained after dehydrogenation

The dehydrogenation reaction was performed in a Schlenk tube under open conditions in order to collect hydrogen gas using a system previously used by us.$^{19}$ The reaction was performed under the catalytic conditions of Table S2, entry 4. After the reaction time, the reaction mixture was allowed to cool to room temperature and then transferred to an autoclave in a glove box. The appropriate amounts of complex 3 and base as described in Table S4 were added to the autoclave and the autoclave was pressurized with hydrogen gas and heated at 135 °C.
8. **Interconversion between the spent fuel and the charged fuel**

The interconversion cycle was started with the hydrogenation of *bis*-cyclic imide (1 mmol) using complex 3 (1 mol%) and KOtBu (3 mol%) in dioxane solvent (2 mL) under 40 bar hydrogen at 135 °C as per the general procedure of hydrogenation described in section 6. 0.5 mmol of mesitylene was also added as an internal standard. The reaction was stopped after 40 hours and analyzed by $^1$H NMR spectroscopy. Complete consumption of the *bis*-cyclic imide was observed. Additionally, formation of 93% 1,4-butanediol and 91% ethylenediamine was also observed. The reaction mixture was then transferred to a Schlenk tube in a nitrogen glove box to which 1 mol% complex 4 and 2 mol% KOtBu was added and the Schlenk tube was heated at 120 °C for 24 h under an open system to collect hydrogen.\(^\text{19}\) After 24 hours, 78 mL of hydrogen gas was collected and $^1$H NMR spectroscopy showed complete conversion of 1,4-butanediol and ethylenediamine. The desired product *bis*-cyclic imide was obtained in 68% yield, the remaining products were detected as lactone (10% yield) and oligoamide (~15% yield). The reaction mixture was then subjected to a second cycle of hydrogenation and dehydrogenation in the same way as described above. The second cycle was started by hydrogenating the mixture of *bis*-cyclic imide, oligoamide and lactone as per the conditions described in Table S4, entry 3. Analysing the reaction mixture by the $^1$H NMR spectroscopy after the hydrogenation step showed the formation of 1,4-butanediol and ethylenediamine in 88% and 85% yields. The reaction mixture was then subjected to the dehydrogenation step under the conditions used in the first cycle, resulting in the formation of 71 mL of hydrogen gas and ~64% of the *bis*-cyclic imide product.
Dehydrogenation cycle

| cycle | Hydrogen | conversion | Product yields |
|-------|----------|------------|----------------|
| 1     | 78 mL    | Diol (99%), diamine (99%) | Imide (68%), lactone (10%) and oligoamide. |
| 2     | 71 mL    | Diol (99%), diamine (99%) | Imide (64%), lactone (12%) and oligoamide. |

Hydrogenation cycle

| cycle | Product yields |
|-------|----------------|
| 1     | 1,4-butanediol (93%), ethylenediamine (91%). |
| 2     | 1,4-butanediol (88%), ethylenediamine (85%). |

9. References

1. Armarego, W. L. F.; Perrin, D. D. *Purification of Laboratory Chemicals*, 4th Edition, Butterworth-Heinemann: Oxford, 2000.
2. Sajid, M.; Jeschke, G.; Wiebcke, M.; Godt, A. *Chem. Eur. J.* 2009, 15, 12960-12962.
3. Zhang, J.; Senthilkumar, M.; Chandra Ghosh, S.; Hyeok Hong, S. *Angew. Chem. Int. Ed*. 2010, 49, 6391-6395.
4. Yuan, Y-C.; Kamaraj, R.; Bruneau, C.; Labasque, T.; Roisnel, T.; Gramage-Doria, R. *Org. Lett.* 2017, 19, 6404-6407.
5. Katritzky, A. R.; Liso, G.; Lunt, E.; Patel, R. C.; Thind, S. S.; Zia, A. *J. Chem. Soc. Perkin Trans. 1*, 1980, 849-851.
6. Dandapani, S.; Curran, D. P. *Tetrahedron*, 2002, 58, 3855-3864.
7. Kato, Y.; Takemoto, M.; Achiwa, K. *Chem. Pharm. Bull.* 1999, 47, 529-535.
8. Patil, S. V.; Mahale, K. A.; Gosavi, K. S.; Deshmukh, G. B.; Patil, N. S. *Org. Prep. Proc. Int.* 2013, 45, 314-320.
9. Bombala, M. U.; Vey, S. V. *J. Chem. Soc., Perkin Trans. 1*, 1979, 3013-3016.
10. Lion, C.; Conceição, L. D.; Hadayatullah, M., *Phosphorus, Sulfur Silicon Relat. Elem.* 2000, 161, 97-113.
11. Houlihan, W. J.; Gogerty, J. H.; Ryan, E. A.; Schmitt, G. *J. Med. Chem.* 1985, 28, 28-31.
12. Bozdoğan, B.; Erşatır, M.; Demirkol, O.; Akbaşlar, D.; Giray, E. S. *Synth. Commun.* 2017, 47, 217-223.
13. Espinosa-Jalapa, N. A.; Kumar, A.; Milstein, D. J. Am. Chem. Soc. 2017, 139, 11722-11725.
14. Zhang, J.; Leitus, G.; Ben-David, Y.; Milstein, D. J. Am. Chem. Soc. 2005, 127, 10840.
15. Balaraman, E.; Gnanaprakasam, B.; Shimon, L. J. W.; Milstein, D. J. Am. Chem. Soc. 2010, 132, 16756.
16. Fogler, E.; Garg, J. A.; Hu, P.; Leitus, G.; Shimon, L. J. W.; Milstein, D. Chem. Eur. J. 2014, 20, 15727-15731.
17. Kumar, A.; Espinosa-Jalapa, N. A.; Leitus, G.; Diskin-Posner, Y.; Avram, L.; Milstein, D. Angew. Chem. Int. Ed. 2017, 56, 14992.
18. Gnanaprakasam, B.; Balaraman, E.; Gunanathan, C.; Milstein, D. J. Polym. Sci., Part A: Polym. Chem. 2012, 50, 1755.
19. Hu, P.; Fogler, E.; Diskin-Posner, Y.; Iron, MA; Milstein, D. Nature Commun, 2015, 6, 6859.