

Minimum costs for producing Hepatitis C Direct Acting Antivirals, for use in large-scale treatment access programs in developing countries

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Summary: Large-scale manufacture of treatment to cure Hepatitis C is feasible, with target prices of US\$100-250 per 12 week treatment course. These low prices could make widespread access to HCV treatment in low and middle income countries a realistic goal.

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Abstract

Background: Several combinations of two or three Direct Acting Antivirals (DAAs) can cure HCV in the majority of treatment-naïve patients. DAAs for HCV infection have similar mechanisms of action and chemical structures to antiretrovirals for HIV infection. Generic antiretrovirals are currently manufactured at very low prices, to treat 10 million people with HIV/AIDS in developing countries.

Methods: Four HCV DAAs, currently either in Phase III development or recent approval (daclatasvir, sofosbuvir, simeprevir, faldaprevir) and ribavirin were classified by chemical structure, molecular weight, total daily dose and complexity of synthesis. The likely range of manufacturing costs per gram of DAA were then projected as formulated product cost, based upon treating a minimum of one million patients annually (to arrive at volume demand) combined with an analysis of the complexity of synthesis and a 40% margin for formulation. Projections were then compared with actual costs of antiretrovirals with similar structures.

Results: Minimum manufacturing costs of antiretrovirals were US\$0.2-2.1/g. The complexity of chemical synthesis for HCV DAAs was ranked from lowest to highest: ribavirin, daclatasvir, sofosbuvir, faldaprevir and simeprevir. Predicted manufacturing costs for 12-week courses of HCV DAAs were: US\$21-63 for ribavirin, US\$10-30 for daclatasvir, US\$68-136 for sofosbuvir, US\$100-210 for faldaprevir, and US\$130-270 for simeprevir.

Conclusions: Within the next 15 years, large-scale manufacture of two or three drug combinations of HCV DAAs is feasible, with minimum target prices of US\$100-250 per 12 week treatment course. These low prices could make widespread access to HCV treatment in low and middle income countries a realistic goal.

Introduction

Worldwide, over 185 million people are infected with Hepatitis C Virus (HCV), with up to 500,000 HCV-related deaths per year.^{1,2} The vast majority of these patients are left untreated, with treatment rates ranging from 3.5% in Europe to 21% in the US.^{3,4}

In comparison, approximately 35.3 million are infected with Human Immunodeficiency Virus (HIV), with 1.6 million HIV-related deaths per year.⁵ The vast majority of these infections and deaths are in resource-limited settings. Due to remarkable progress in reducing costs of treatment, over ten million patients are now on antiretroviral (ARV) regimens in low- and middle-income countries.⁵

People with Hepatitis C infection can be cured using modern treatment, but at a very high cost. The US launch prices for 12 weeks treatment with simeprevir and sofosbuvir, two newly approved drugs, are US\$66,000 and US\$84,000, respectively.⁶ In low and middle income countries, access to HCV treatment is extremely limited, mainly because of the complexity of patient management and high costs.⁷ Of the twenty countries with the largest HCV epidemics, twelve are classified as low or lower-middle income (Table 1). For widespread treatment of HCV in developing countries to become feasible, we will need short-course antiviral treatment available at very low costs and with minimal diagnostic support.

Recently, a number of direct acting antivirals (DAAs) in Phase 2 or 3 development have shown sustained virological response (SVR) rates of up to 100% in non-cirrhotic patients and, promisingly, high SVR rates in people with advanced liver disease or previous null response (Table 2). The approval of such drugs will likely see DAA combinations replace interferon-based regimens as the new standard of care.¹⁸ Success of treatment often depends on genotype and while the majority of results are from clinical trials carried out on patients infected with the HCV-1 genotype, encouraging results are emerging for the treatment of both HCV-2 and HCV-3 (Table 2).

DAAs for HCV infection have similar mechanisms of action and chemical structures to antiretrovirals currently in use for the treatment of HIV. These drugs are also similarly intended for oral delivery

using relatively uncomplicated formulation technologies. Over the last two decades, generic competition, increased purchase volumes, and improvements in manufacturing processes (both API and formulation) have driven the cost of HIV antiretroviral treatment down by over 99%, with standard triple therapy now costing as little as US\$60 per patient per year.¹⁹

These prices could not have been imagined when triple antiretroviral drug combinations were introduced at over US\$10,000 per patient/year in the late 1990s.⁷ Following the important precedent set by access to treatment for HIV infection, the aim of this analysis was to estimate the minimum cost of HCV treatment, assuming the same strategic market dynamics as used to supply antiretrovirals to people with HIV/AIDS in developing countries.

Methods

In this analysis, the molecular structures of HCV DAAs were compared with their closest analogues in the treatment of HIV. We evaluated the likely routes of manufacturing as published by the originator companies and assumed a volume demand based on 1-5 million patients per year to arrive at approximate costs of DAA active pharmaceutical ingredients (APIs). We then added on a 40% margin for finished production manufacturing (formulation) to arrive at a projected cost of therapy.

The purpose of this analysis is to logically speculate whether DAAs can be provided for millions of people at a reasonable cost. The analysis is not meant to be exact or to arrive at a “most likely optimised cost” for any individual or combination DAA therapy. Very little information is presently available to estimate actual commercial formulation costs for DAAs. These DAAs are all delivered orally using conventional technologies. Projected API costs for these DAAs range from US\$1,400-21,000/kg; as such the very high relative costs of API would justify a 40% increment as a reasonable add-on for estimating cost of the finished dosage form.

The minimum treatment costs of comparator HIV antiretrovirals were calculated using the lowest prices reported by manufacturers to Médecins Sans Frontières in 2012.¹⁹ Minimum costs per gram

of ARVs ranged from US\$0.20 to US\$0.90/g for nucleoside analogues, US\$0.50/g for nucleotide analogues, and US\$0.70-2.10/g for protease inhibitors (Table 3).

Four HCV DAAs were included in this study: daclatasvir (Phase III), sofosbuvir (approved December 2013), faldaprevir (Phase III), and simeprevir (approved November 2013). Ribavirin, already available as a generic, was also included in this analysis due to its likely inclusion in future drug regimens. Using the most likely daily dosage identified from clinical trials, the total drug requirement for each DAA was calculated for a 12 week course of each HCV DAA. In order to estimate the manufacturing cost of each HCV DAA, current routes of synthesis and critical cost-limiting raw materials were taken from the patent literature. In an alternative comparison, each compound was matched to the closest equivalent HIV ARV based on structural similarity.

Production costs per gram of HCV DAA were assumed to be 1-10 times higher than the equivalent HIV ARV dependant on the complexity of chemical synthesis. Complexity was assessed by identifying the most likely cost-limiting intermediates for the synthesis of each DAA. Additional considerations included ease and number of steps of manufacture and availability and cost of starting materials. Using this estimate for the production cost per gram of drug together with the total drug requirement, an estimate for the minimum cost of a 12 week course of treatment with each HCV DAA was calculated. These costs were used to provide estimates for the production costs of 2- or 3-drug combination therapy based on the combinations currently being investigated in clinical trials (Table 2).

Results

Based on molecular weight, chemical structure, class, and dose, the HIV ARV most comparable to each HCV DAA were as follows: zidovudine to ribavirin, atazanavir to daclatasvir, tenofovir and stavudine to sofosbuvir, darunavir to faldaprevir, and lopinavir to simeprevir. Table 4 shows the HCV DAA and most comparable HIV antiretroviral as well as the likely cost limiting raw materials in production. A summary of the estimated costs per person for a 12 week course of each HCV DAA is shown in Table 5.

Ribavirin

With a daily dose of 1000-1200mg dependent on patient weight, a 12-week course of treatment with ribavirin will require between 84.0 and 100.8 grams of API. This results in a range of demand between 84 and 504 metric tonnes of API to treat between 1-5 million patients. Ribavirin is a nucleoside analogue with a molecular weight of 244g/mol. Based on this and the chemical formula (Table 3), zidovudine was considered to be the closest equivalent HIV relative of ribavirin (also a nucleoside analogue with molecular weight 267g/mol). Analysis revealed that ribavirin has a relatively simple chemical synthesis.²⁰ Using zidovudine alongside knowledge of the current costs of ribavirin, production costs were estimated to lie between US\$0.26 and US\$0.41 per gram, giving potential costs for a 12-week course of ribavirin of US\$34-48 for the dose of 1000mg per day, and US\$41-58 for the dose of 1200mg/day.

Daclatasvir

At the dose of 60mg/day, a 12-week course of treatment would require 5.0 grams of daclatasvir API. Daclatasvir is a NS5A inhibitor with molecular weight 739g/mol. Treating 1-5 million patients with daclatasvir would require 5-25 metric tonnes of API. Daclatasvir was deemed most structurally comparable to atazanavir, a protease inhibitor with molecular weight 705g/mol (Table 3). Daclatasvir has a straightforward synthesis with the cost-limiting intermediate being the substituted biphenyl compound shown (Table 5).^{21,22} There is wide availability of cheap starting materials to synthesise the side-chains of daclatasvir. The estimated production costs of daclatasvir finished product are between US\$2 and US\$6 per gram. At a daily dose of 60mg, the estimated production costs for a 12-week course of treatment were between US\$10-US\$30.

Sofosbuvir

Delivered at a 400 mg daily dose, a 12-week course of treatment with sofosbuvir will require 33.6 grams of API. This results in a range of API demand between 33.6 and 168 metric tonnes to treat 1-5 million patients. With a molecular weight of 529g/mol and chemical formula of $C_{22}H_{29}FN_3O_9P$, sofosbuvir was considered most structurally comparable to tenofovir, with a molecular weight of

636g/mol and chemical formula $C_{23}H_{34}N_5O_{14}P$ (Table 3). The cost-limiting raw material/intermediate for the synthesis of sofosbuvir API is the 2'-fluoro-2'-methylfuranose intermediate (Table 5).^{23,24,25} Although a number of approved drugs have similar structures, the presence of both a methyl and a fluoro substituent at the 2' position makes this intermediate cost-limiting. We have estimated API production costs for sofosbuvir between US\$2 and US\$4 per gram; sofosbuvir is considered most closely analogous in cost to the HIV drug stavudine, which is relatively expensive in terms of manufacturing costs per gram. An estimated cost for 12 weeks of treatment with sofosbuvir API is US\$68-136.

Faldaprevir

At a daily dose of 120 mg, 10.1 grams of faldaprevir API will provide a 12-week course of treatment. Treating 1-5 million patients with Faldepraver would require 10.1-50.5 metric tonnes of API. Faldaprevir is a protease inhibitor with a molecular weight of 870g and chemical formula of $C_{40}H_{49}BrN_6O_9S$ (Table 3). As a result of this high molecular weight and complicated chemical structure darunavir was deemed the most cost-comparable with faldaprevir. Faldaprevir manufacture requires a tetra-substituted quinoline and a vinyl-cyclopropane amino acid as raw materials for the synthesis of the API (Table 5).^{25,26} Due to the difficult synthesis, estimated production costs of US\$10-21 per gram were applied. Accordingly, a 12-week course of treatment with faldaprevir could cost between US\$100 and US\$210.

Simeprevir

At a daily dose of 150 mg, a course of treatment with simeprevir would require 13 grams of simeprevir API. Treating 1-5 million patients with Simepraver would require 13-65 tonnes of API. In terms of class, molecular weight and chemical structure, lopinavir/r was considered the equivalent HIV ARV of simeprevir, although atazanavir was included in comparing cost estimates (Table 3). Simeprevir is a medium-ring macrocycle that utilises a ring-closing metathesis reaction in the late stages of API manufacturing, which is challenging (Table 5). Novel raw materials entered into the synthesis include a tetra-substituted quinoline and the same vinyl-cyclopropane amino acid as used

in the synthesis of faldaprevir.²⁷ Production costs were estimated at US\$10 to US\$21 per gram, giving an estimated cost of treatment of US\$130-270 for 12 weeks.

Combination therapies

Table 6 shows the estimated prices of combination therapy based on the DAA drug prices calculated in this analysis. Using the minimum costs, a 12-week course of treatment with daclatasvir and sofosbuvir could cost a minimum of US\$78 per person. A treatment with sofosbuvir and simeprevir could cost US\$198 for 12 weeks with the addition of ribavirin increasing this cost to US\$219 per person. For some patients or some regimens, a 24-week treatment might be necessary, doubling treatment costs.

Discussion

Fifteen years ago, universal access to antiretroviral therapy for HIV/AIDS in developing countries was considered too complex and expensive to be feasible. With the invention of effective, simple therapy, a market was created for generic competition that in turn made treatment affordable, and along with the associated international funding, treatment scale up became possible.²⁸ The situation of HCV treatment today is reminiscent of treatment for HIV/AIDS in the year 2000.

Our analysis suggests that 2 or 3 drug combinations of interferon-free HCV treatments could cost US\$100-250 for a 12 week course of treatment. These low prices coupled with the high SVR rates established in several trials shows the potential for large-scale, low cost HCV treatment in developing countries, with the potential to repeat the model of low-cost HIV treatment that has benefitted millions of people. This model of treatment is based on simplified, standardised treatment approaches using tolerable, easy-to-administer regimens that are supportive of task shifting (care delivery by lesser trained health staff) and good patient adherence, and could be facilitated by widespread access to oral, short-course DAA therapy in low income countries.²⁹

The cost of production of HIV antiretrovirals has fallen progressively over the past decade through increased market competition, increased volumes, and efficiencies in manufacturing processes. The

Clinton Health Access Initiative pioneered purchasing from quality-assured generic pharmaceutical manufacturers in India and raw material manufacturers in China to ensure the lowest sustainable costs for some antiretrovirals, lowering prices dramatically.³⁰ Our estimated unit costs of HCV DAAs per gram are still far higher than the current costs of HIV antiretrovirals, and it could be assumed that the cost of HCV DAAs may further decrease over time through process optimisation and the cheaper sourcing of raw materials as volume demand drives competition and process efficiencies.

We have been conservative in our estimations versus the history of costs for HIV drug production. API syntheses begin with raw materials of rather simple structure that are combined in a specific and modular fashion to build the more complex structures of drugs. When a commercial market already exists for these raw materials, their contribution to cost is rather modest. When raw materials with no previous commercial demand are used, these can contribute very substantially to cost. Efavirenz, an HIV-1 reverse transcriptase inhibitor, provides an illustration of this.

Cyclopropylacetylene (CPA) is a raw material for the synthesis of efavirenz. During human clinical trials, when the demand for CPA was only a few metric tonnes, CPA cost was US\$800-1350/kg. When the drug was approved (1998) and demand for CPA was about 50 tonnes per year, the price of CPA had fallen to US\$300-350/kg. Today, with a global demand for efavirenz of over 800 tonnes/year, CPA can be purchased for US\$50-60/kg. Efavirenz was launched in 1998 at an API cost of \$1800/kg. The current best cost for the API is about \$120/kg from Indian generic suppliers.

The DAA molecules in this analysis each contain at least one novel raw material that will be expensive in the early phases of commercial introduction. Similar to the reductions in the cost of efavirenz, the estimated costs in this analysis can only be justified if we can guarantee the eventual procurement of large orders. With the DAAs investigated in this study, twelve weeks treatment for one million patients would require between 5 and 34 metric tonnes of API, with ribavirin requiring between 84 and 101 tonnes of active ingredient. Treatment for only a fraction of the 185 million people infected with HCV could ensure order sizes in a similar region to HIV antiretrovirals.

With the introduction of these new HCV DAAs, the methods used to diagnose and monitor HCV are likely to be greatly simplified.³¹ In order to ensure widespread treatment, the costs of diagnostic and monitoring tests will also need to fall. In the same way that the cost of HIV treatment has decreased, the cost of HIV diagnostics and monitoring has rapidly declined over the last few decades with commercial HIV RNA tests now costing less than US\$2 per test.³²

There are several limitations with this analysis. Firstly, in order to calculate more precise costs, more detailed analysis of the API and formulation processes for production will be necessary. Very little specific information is currently available about formulations of the DAAs. However, all of the DAAs are for oral delivery and – to the best available knowledge – use relatively common drug release technologies. This is in parallel with the formulation of ARVs. Given this, we applied a 40% conversion cost of API to finished product, noting that this figure is not exceeded for any of the large-scale ARV combinations being marketed. Secondly, access to the HCV DAAs at minimum prices in developing countries will strongly depend on the level of enforcement of patent restrictions. These price estimates are based on the previous experience with production of ARVs for HIV treatment which assumes market competition through generic manufacture. Legal mechanisms such as voluntary or compulsory licenses may be needed to overcome patent barriers and stimulate such competition. Patents for daclatasvir,³³ sofosbuvir,³⁴ faldaprevir,^{35,36} and simeprevir will remain in force until at least 2025,³⁷ after which time it should be possible to produce generic versions at much lower cost, provided no additional patents are granted for modifications such as route of synthesis, crystalline structures or methods of use. Such ‘evergreen’ patenting has happened repeatedly in HIV drug development and could further delay the introduction of generic DAAs.^{19,38} In the near future, there need to be negotiations with the patent holders on voluntary licensing, access prices for low and middle income countries, and mass production of low cost DAAs. Unless these DAAs are widely introduced, current death rates from HCV of 500,000 people per year will continue for many years to come.

Finally, our analysis is limited to HCV DAAs that have been mainly evaluated in genotype 1 HCV. Although sofosbuvir has recently been approved in combination with ribavirin for the treatment of

genotypes 2 and 3, further research needs to be conducted to ensure pan-genotypic coverage of HCV.

The high cost of drugs is often justified by the need to recover costs of research and development (R&D). In the case of antiretrovirals for HIV, many of these costs were assumed by the public sector, where parts of the drug discovery and development occurred.³⁹ Several mechanisms have been used by originator companies to allow access to antiretrovirals in low-income settings. These include differential pricing (charging more in high-income countries) and voluntary licensing (allowing third party generic manufacture). Similar mechanisms could be employed for HCV DAAs to ensure these drugs are affordable, while also providing a financial return on the costs of research and development.⁴⁰ Commitments by national governments to scale up antiretroviral therapy, with support from international donors, were also critical to leveraging prices by increasing the size and predictability of the HIV market. This will be an essential factor in lowering drug prices and increasing access to HCV DAAs.⁴¹

Expanding access through greater affordability will also confer indirect benefits. Currently a large proportion of untreated patients continue to spread the HCV pandemic worldwide. Lessons learnt from HIV suggests that with the introduction of strong community programmes for testing, and high rates of treatment coverage and retention, expanded access to treatment is also likely to have a pronounced effect on HCV transmission, a benefit already suggested in modelling studies.⁴²

Widespread access to HCV DAAs will also require fast regulatory approvals of new drugs, political will, establishment of national viral hepatitis programs, early access programs to start treating people who are most at risk, and accepted international HCV treatment guidelines.

In conclusion, widespread access to combinations of HCV DAAs is feasible, with potential target prices of US\$100-250 per person for a 12 week treatment course. Progressive reductions in these costs are likely through optimisation of chemical synthesis and cheaper sourcing of raw materials. These low prices could make widespread access to HCV treatment in low and middle income countries a realistic goal, with substantial individual and public health benefits.

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Authors' contributions: Andrew Hill wrote the original plan for analysis and coordinated the project. Bryony Simmons conducted the literature search and compiled the data for analysis. Joe Fortunak worked on the routes of chemical synthesis and raw materials. Nathan Ford worked on the patent access issues. Saye Khoo worked on the clinical issues in treatment of Hepatitis C. All authors critically reviewed the manuscript and approved the final version.

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Table 1. Hepatitis C global prevalence by country (2010)

Country	Income classification	Most prevalent genotypes	Anti-HCV* (%)	No. infected
China	Upper-middle	1,2,6	2.2	29,791,212
India	Lower-middle	1,3	1.5	18,216,960
Egypt	Lower-middle	4	14	11,826,360
Indonesia	Lower-middle	1,2	3.9	9,436,986
Pakistan	Lower-middle	3	5.9	9,422,402
Russia	Upper-middle	1,3	4.1	5,796,498
USA	High	1,2,3	1.8	5,367,834
Democratic Republic of Congo	Low	4	6.4	4,010,240
Nigeria	Lower-middle	1,2	2.1	3,323,439
Japan	High	1,2	2.4	3,058,008
Cameroon	Lower-middle	1,2,4	13.8	2,754,204
Brazil	Upper-middle	1,3	1.4	2,609,670
Uganda	Low	1,4	6.6	2,230,536
Philippines	Lower-middle	1	2.2	1,932,854
Italy	High	1,2	3.2	1,923,136
Ukraine	Lower-middle	1	4.0	1,864,840
Uzbekistan	Lower-middle	1,3	6.5	1,774,955
Turkey	Upper-middle	1	2.2	1,549,108
Ethiopia	Low	1,2,4	1.9	1,500,734
Thailand	Upper-middle	1,3,6	2.2	1,499,058
World's Population			2-3%	160-180 million

Sources: Lavanchy 2011⁸ & Alberti & Negro 2011⁹ Income classifications from The World Bank, 2013.

*Prevalence of antibody to HCV

Table 2. Results from clinical trials of interferon-free regimens

Combination	Study population	Previous response	Geno-type	Treatment arms	SVR rate				
Daclatasvir + sofosbuvir +/- RBV	AI444-040 ¹⁰ Non-cirrhotic (n=170)	Naïve	1	12wk (n=82)	95-98% (SVR-4)				
				24wk (n=44)	93-100% (SVR-24)				
			2&3	24wk (n=44)	88-100% (SVR-24)				
Daclatasvir + asunaprevir + BMS-791325	AI443-014 ¹¹ Non-cirrhotic (n=32)	Naïve	1	24wk (n=16)	94% (SVR-4)				
				12wk (n=16)	94% (SVR-12)				
Daclatasvir + asunaprevir	AI447-011 ¹² (n=38)	Null response	1b	Once-daily (n=20)	65% (SVR-12)				
				Twice-daily (n=18)	78% (SVR-12)				
Sofosbuvir + RBV +/- GS-5885	ELECTRON ¹³ Non-cirrhotic (n=120)	Naïve	1	12wk, 3-drug (n=25)	100% (SVR-12)				
				12wk, 2-drug (n=25)	84% (SVR-12)				
				12wk, 3-drug (n=9)	100% (SVR-12)				
			2&3	12wk, 2-drug (n=11)	100% (SVR-24)				
				8wk, 2-drug (n=25)	64% (SVR-12)				
Experienced	12wk, 2-drug (n=25)	68% (SVR-12)							
Sofosbuvir + weight-based RBV or low-dose RBV	SPARE ¹⁴ Non-cirrhotic (n=10) All stages fibrosis (n=50)	Naïve	1	24wk, non-cirrhotic, WB (n=10)	90% (SVR-12)				
				24wk, WB [†] (n=25)	72% (SVR-4)				
				24wk, LD [†] (n=25)	56% (SVR-4)				
Sofosbuvir + RBV	POSITRON ¹⁵ (n=207 +71 placebo)	IFN-ineligible	2	12wk (n=109)	93% (SVR-12)				
				3	12wk (n=98)	61% (SVR-12)			
			3	12wk (n=36)	86% (SVR-12)				
16wk (n=32)	94% (SVR-12)								
Sofosbuvir + RBV	FUSION ¹⁵ (n=201)	Experienced	2	12wk (n=64)	30% (SVR-12)				
				3	16wk (n=63)	62% (SVR-12)			
			2	24wk, 3-drug (n=24)	67% (SVR-8)				
24wk, 2-drug (n=15)	100% (SVR-8)								
Sofosbuvir + simeprevir +/- RBV	COSMOS ¹⁶ Non-cirrhotic (n=80)	Null response	1	12wk, 3-drug (n=27)	96% (SVR-8)				
				12wk, 2-drug (n=14)	93% (SVR-8)				
				Faldaprevir + BI207127 +/- RBV	SOUND-C2 ¹⁷ (n=329 [33=F4])	Naïve	1	28wk, 3-drug (n=316)	Up to 69% (SVR-12)
								28wk, 2-drug (n=46)	39% (SVR-12)

SVR-4: undetectable HCV RNA 4 weeks after finished treatment

SVR-12: undetectable HCV RNA 12 weeks after finished treatment

SVR-24: undetectable HCV RNA 24 weeks after finished treatment

*Weight-based, †Low-dose

Table 3. Minimum costs of HIV antiretrovirals, by increasing cost per gram

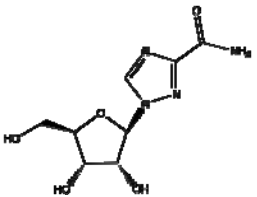
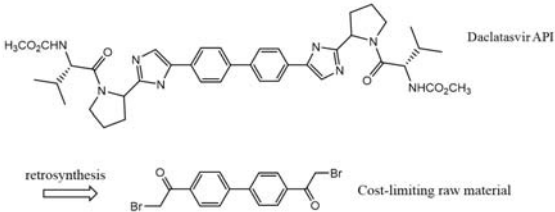
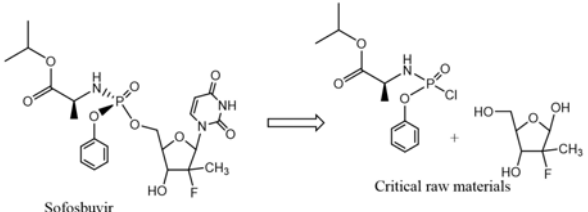
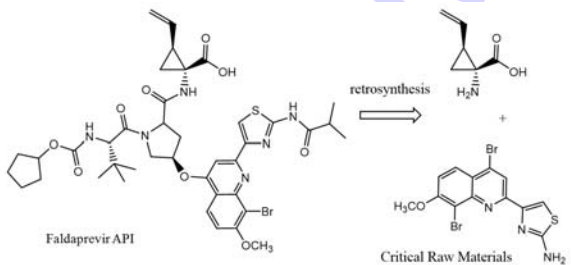
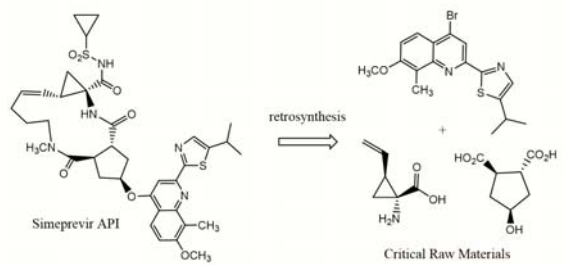
Agent	Chemical formula	Molecular weight (g/mol)	Daily dose (mg)	Overall dose per year (g)	Cost per gram (US\$)	Cost per year (US\$)
Lamivudine	C ₈ H ₁₁ N ₃ O ₃ S	229	300	110	0.19	21
Zidovudine	C ₁₀ H ₁₃ N ₅ O ₄	267	600	219	0.34	75
Tenofovir disoproxil fumarate	C ₂₃ H ₃₄ N ₅ O ₁₄ P	636	300	110	0.52	57
Indinavir*	C ₃₆ H ₄₇ N ₅ O ₄	614	1600	584	0.67	394
Abacavir	C ₁₄ H ₁₈ N ₆ O	286	600	219	0.77	169
Emtricitabine	C ₈ H ₁₀ FN ₃ O ₃ S	247	200	73	0.79	58
Stavudine	C ₁₀ H ₁₂ N ₂ O ₄	224	60	22	0.86	19
Lopinavir/ritonavir ⁺	C ₃₇ H ₄₈ N ₄ O ₅	629	800/200 = 1000	365	1.01	368
Darunavir*	C ₂₇ H ₃₇ N ₃ O ₇ S	548	1200	438	1.83	803
Saquinavir*	C ₃₈ H ₅₀ N ₆ O ₅	671	2000	730	1.87	1366
Atazanavir*	C ₃₈ H ₅₂ N ₆ O ₇	705	300	110	2.11	231

Source: Untangling the web of antiretroviral price reductions (MSF).¹⁹

+ chemical formula and molecular weight for lopinavir only

*Prices of protease inhibitors do not include the cost of the ritonavir booster drug, except for lopinavir/ritonavir

Table 4. HCV DAA structure and likely cost limiting raw material in production

HCV DAA agent	HCV DAA structure and retrosynthesis	Comparator HIV agent
Ribavirin $C_8H_{12}N_4O_5$ MW: 244g/mol		Zidovudine $C_{10}H_{13}N_5O_4$ MW: 267g/mol
Daclatasvir $C_{40}H_{50}N_8O_6$ MW: 739g/mol		Atazanavir $C_{38}H_{52}N_6O_7$ MW: 705g/mol
Sofosbuvir* $C_{22}H_{29}FN_3O_9P$ MW: 529g/mol		TDF $C_{23}H_{34}N_5O_{14}P$ MW: 636g/mol
Faldaprevir $C_{40}H_{49}BrN_6O_9S$ MW: 870g/mol		Darunavir $C_{27}H_{37}N_3O_7S$ MW: 548g/mol
Simeprevir $C_{38}H_{47}N_5O_7S_2$ MW: 750g/mol		Lopinavir/r $C_{37}H_{48}N_4O_5$ MW: 629g/mol

* Sofosbuvir is presumably synthesized as a mixture of diastereomers on phosphorous. Only one of these two diastereomers is desired in the API. Separation of diastereomers can be a substantial contributor to the cost of API production, particularly when an undesired diastereomer cannot be efficiently recycled. See US Patent 7,390,791 and US Application 20130065856 for the tenofovir alafenamide fumarate (TAF) prodrug version of tenofovir which contains an identical "ProTide™"

moiety as that present in Sofosbuvir. Efficient recycling of diastereomers has been demonstrated for TAF, but we do not presume this is the case for Sofosbuvir.

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Table 5. Predicted minimum costs of HCV DAAs

Agent	Daily dose (mg)	Overall dose per 12wks (g)	Estimated cost per gram (US\$)	Predicted cost (US\$)
Ribavirin	1000-1200	84-101	0.26-0.41*	\$34-48**
Daclatasvir	60	5	2-6	\$10-30
Sofosbuvir	400	34	2-4	\$68-136
Faldaprevir	120	10	10-21	\$100-210
Simeprevir	150	13	10-21	\$130-270

*current range of API cost per gram from 3 Chinese suppliers

**shows cost for 1000mg daily dose; \$41-58 for 1200mg daily dose of ribavirin; adjusted with a 40% markup for formulation.

Table 6. Potential regimen costs

Regimen	Duration (weeks)	Predicted cost (US\$)
Daclatasvir + Sofosbuvir	12	78-166
Daclatasvir + Sofosbuvir + Ribavirin	12	112-214
Sofosbuvir + Ribavirin	12	102-184
Sofosbuvir + Simeprevir	12	198-406
Sofosbuvir + Simeprevir + Ribavirin	12	232-454

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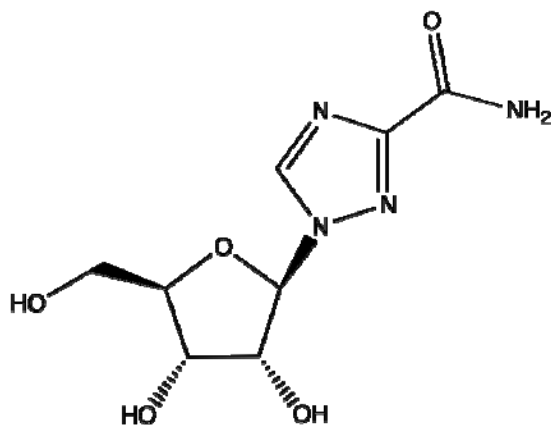
References

- 1 Mohd Hanafiah K, Groeger J, Flaxman AD, Wiersma ST. Global epidemiology of hepatitis C virus infection: new estimates of age-specific antibody to HCV seroprevalence. *Hepatology* 2013; **57(4)**: 1333-42.
- 2 Lozano R, Naghavi M, Foreman K, et al. Global and regional mortality from 235 cause of death for 20 age groups in 1990 and 2010: a systematic analysis for the Global Burden of Disease Study 2010. *Lancet* 2012; **380(9859)**: 2095-128.
- 3 Razavi H, Estes C, Pasini K, Gower E, Hindman S. HCV treatment rate in select European countries in 2004-2010. *J Hepatol.* 2013; **58(Suppl 1)**: S22-23.
- 4 Volk ML. Antiviral therapy for hepatitis C: why are so few patients being treated? *J Antimicrob Chemother.* 2010; **65(7)**: 1327-9.
- 5 World Health Organisation. HIV/AIDS fact sheet. Updated Oct 2013. Available from: <http://www.who.int/hiv/en/> [accessed 8 November 2013].
- 6 Fair Pricing Coalition. Activists condemn Gilead for exorbitant price of its new hepatitis C drug. 9 December 2013. Available from: <http://www.thebody.com/content/73462/activists-condemn-gilead-for-exorbitant-price-of-t.html> [accessed 11 December 2013].
- 7 Ford N, Singh K, Cooke GS, et al. Expanding access to treatment for hepatitis C in resource-limited settings: lessons from HIV/AIDS. *Clin Infect Dis.* 2012; **54(10)**: 145-72.
- 8 Lavanchy D. Evolving epidemiology of hepatitis C virus. *Clin Microbiol Infect.* 2011; **17(2)**: 107-15.
- 9 Negro F, Alberti A. The global health burden of hepatitis C virus infection. *Liver Int.* 2011; **Suppl 2**: 1-3.
- 10 Sulkowski MS, Gardiner DF, Rodriguez-Torres M, et al.; A1444040 Study Group. High rate of sustained virologic response with the all-oral combination of daclatasvir (NS5a inhibitor) plus sofosbuvir (nucleotide NS5b inhibitor) with or without ribavirin, in treatment-naïve patients chronically infected with HCV GT 1, 2, or 3. Paper presented at: 63rd Annual Meeting of the

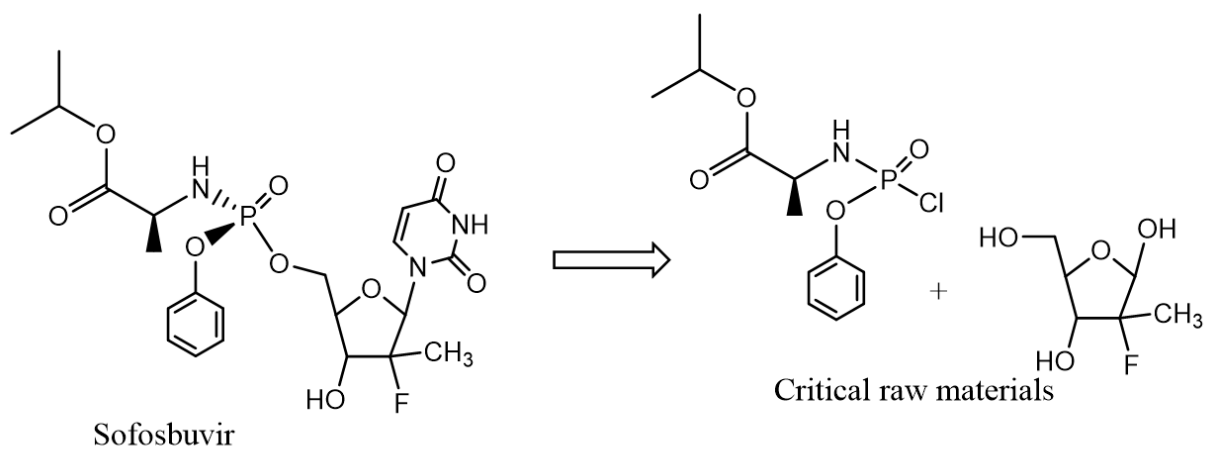
- American Association for the Study of Liver Diseases (AASLD)*. 2012; Nov 9-12: Boston, MA.
- 11 Everson GT, Sims KD, Rodriguez-Torres M, et al. An interferon-free, ribavirin-free 12-week regimen of daclatasvir (DCV), asunaprevir (ASV), and BMS-791325 yielded SVR4 of 94% in treatment-naïve patients with genotype (GT) 1 chronic hepatitis C virus (HCV) infection. Paper presented at: *63rd Annual Meeting of the American Association for the Study of Liver Diseases (AASLD)*. 2012; Nov 9-12: Boston, MA.
 - 12 Lok DF, Gardiner DF, Hezode C, et al. Sustained virologic response in chronic HCV genotype (GT) 1-infected null responders with combination of daclatasvir (DCV; NS5A inhibitor) and asunaprevir (ASV; NS3 inhibitor) with or without peginterferon alfa-2a/ribavirin (PEG/RBV). *Hepatology* 2012; **56(S1)**: 230A-1A.
 - 13 Gane EJ, Stedman CA, Hyland RH, et al. Once daily sofosbuvir (GS-7977) regimens in HCV genotype 1-3: The ELECTRON trial. *Hepatology* 2012; **56(S1)**: 306A-7A
 - 14 Osiunusi A, Heytens L, Lee YJ, et al. High efficacy of GS-7977 in combination with low or full dose ribavirin for 24 weeks in difficult to treat HCV infected genotype 1 patients. Paper presented at: *63rd Annual Meeting of the American Association for the Study of Liver Diseases (AASLD)*. 2012; Nov 9-12: Boston, MA.
 - 15 Jacobson IM, Gordon SC, Kowdley KV, et al. Sofosbuvir for hepatitis C genotype 2 or 3 in patients without treatment options. *N Engl J Med*. 2013; **368(20)**: 1867-77.
 - 16 Lawitz E, Ghalib R, Rodriguez-Torres M, et al. COSMOS Study: SVR4 results of a once daily regimen of simeprevir (TMC435) plus sofosbuvir (GS-7977) with or without ribavirin in HCV genotype 1 null responders. Paper presented at: *20th Conference on Retroviruses and Opportunistic Infections*. 2013; March 3-6: Atlanta, GA.
 - 17 Zeuzem S, Soriano V, Asselah T, et al. Interferon (IFN)-free combination treatment with the HCV NS3/4A protease inhibitor faldaprevir (BI 201335) and the non-nucleoside NS5B inhibitor BI 207127 ± ribavirin: final results of SOUND-C2 and predictors of response. *Hepatology* 2012; **56(S1)**: 308A-9A.
 - 18 Nature Medicine. A brighter future in the fight against hepatitis. *Nat Med*. 2013; **19(7)**: 791.

- 19 MSF Drug Access Team. Untangling the web of antiretroviral price reductions. 15th edition, Geneva, July 2012. Available from: <http://www.msfacecess.org/reports> [accessed June 2013].
- 20 Witkowski JT, Robins RK, Sidwell RW, Simon LN. Design, synthesis, and broad spectrum antiviral activity of 1-D-ribofuranosyl-1,2,4-triazole-3-carboxamide and related nucleosides. *J Med Chem.* 1972; **15(11)**: 1150-4.
- 21 Gao M, Nettles RE, Belema M, et al. Chemical genetics strategy identifies an HCV NS5A inhibitor with a potent clinical effect. *Nature* 2010; **465(7294)**: 96-100.
- 22 Peng G, Hamm J, Pack SK, et al.; Bristol-Myers Squibb Company. Process for synthesising compounds useful for treating hepatitis C. *Patent Application WO2009/020825 A1*. Feb 12, 2009.
- 23 Chun BK, Wang P.; Pharmasset, Inc. Preparation of 2'-fluoro-2'-alkyl-substituted or other optionally substituted ribofuranosyl pyrimidines and purines and their derivatives. *Patent Application WO2006/031725 A3*. Apr 16, 2009.
- 24 Chun BK, Pamulapati GR, Rachakonda S, et al.; Pharmasset, Inc. Nucleoside phosphoramidates. *Patent Appliation US2011/0251152 A1*. Oct 13, 2011.
- 25 White PW, Llinàs-Brunet M, Amad M, et al. Preclinical characterization of BI 201335, a C-terminal carboxylic acid inhibitor of the hepatitis C virus NS3-NS4A protease. *Antimicrob Agents Chemother.* 2010; **54(11)**: 4611-8.
- 26 Llinàs-Brunet M, Bailey MD, Goudreau N, et al. Discovery of a potent and selective noncovalent linear inhibitor of the hepatitis C virus NS3 protease (BI 201335). *J Med Chem.* 2010; **53(17)**: 6466-76.
- 27 Horvath A, Wuyts S, Depré D, et al.; Janssen Pharmaceuticals, Inc. Improved process for preparing an intermediate of the macrocyclic protease inhibitor TMC435. *Patent Application WO2013/061285 A1*. May 2, 2013.
- 28 Schwartländer B, Grubb I, Perriëns J. The 10-year struggle to provide antiretroviral treatment to people with HIV in the developing world. *Lancet* 2006; **368(9534)**: 541-6.
- 29 Gilks CF, Crowley S, Ekpini R, et al. The WHO public-health approach to antiretroviral treatment against HIV in resource-limited settings. *Lancet* 2006; **368(9534)**: 505-10.

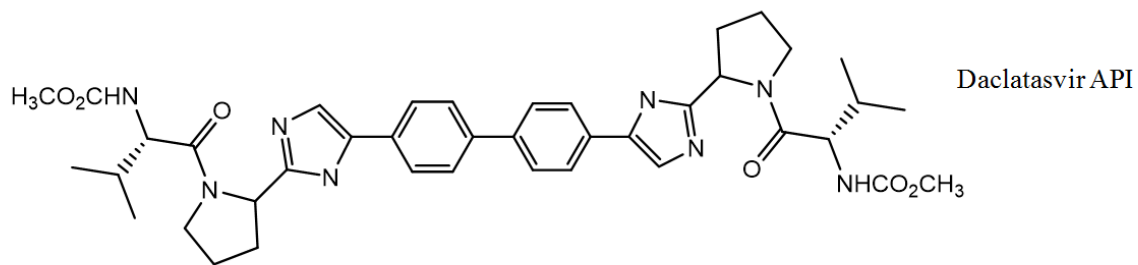
- 30 The Clinton Health Access Initiative. Antiretroviral (ARV) ceiling price list. May 2013. Available from: <http://www.clintonhealthaccess.org/news-and-information/key-CHAI-documents> [accessed 20 June 2013].
- 31 MSF Access Campaign. The diagnosis and treatment of hepatitis C: a technical landscape. Geneva, April 2013. Available from: <http://www.msfacecess.org/our-work/hiv-aids/article/2024> [accessed 20 June 2013].
- 32 Wu G, Zaman MH. Low-cost tools for diagnosing and monitoring HIV infection in low-resource settings. *Bull World Health Organ.* 2012; **90**: 914-20.
- 33 Bristol-Myers Squibb Company. Form 10-K: Annual report pursuant to section 13 or 15(d) of the securities exchange act of 1934. Fiscal year ending Dec 31, 2011. Page 9.
- 34 Pharmasset, Inc. Form 10-K: Annual report pursuant to section 13 or 15(d) of the securities exchange act of 1934. Fiscal year ending Sep 30, 2011. Page 26.
- 35 Llinàs-Brunet M, Bailey MD Bhardwaj P, et al.; Boehringer Ingelheim International. Hepatitis C inhibitor compounds. *Patent Application: US7585845 B2.* Sep 8, 2009.
- 36 Busacca CA, Frutos RP, Haddad N, et al.; Boehringer Ingelheim International. Process for preparing acyclic HCV protease inhibitors. *Patent Application: US7514557 B2.* Apr 7, 2009.
- 37 Medivir. 2012 Annual Report. Stockholm, 2012. Page 26.
- 38 Kapczynski A. Engineered in India – Patent Law 2.0. *N Engl J Med.* 2013; **369**: 497-9.
- 39 Chirac P, von Schoen-Angerer T, Kasper T, Ford N. AIDS: patent rights versus patient's rights. *Lancet* 2000; **356**: 502
- 40 Moon S, Jambert E, Childs M, von Schoen-Angerer T. A win-win solution?: A critical analysis of tiered pricing to improve access to medicines in developing countries. *Global Health* 2011; **7**: 39.
- 41 Holmes C, Coggin W, Jamieson D, et al. Use of generic antiretroviral agents and cost savings in PEPFAR treatment programs. *JAMA* 2010; **304**: 313-20.
- 42 Durier N, Nguyen C, White LJ. Treatment of hepatitis C as prevention: a modelling case studying in Vietnam. *PLoS One* 2012; **7(4)**: e34548.



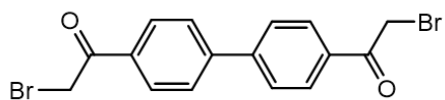
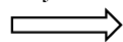
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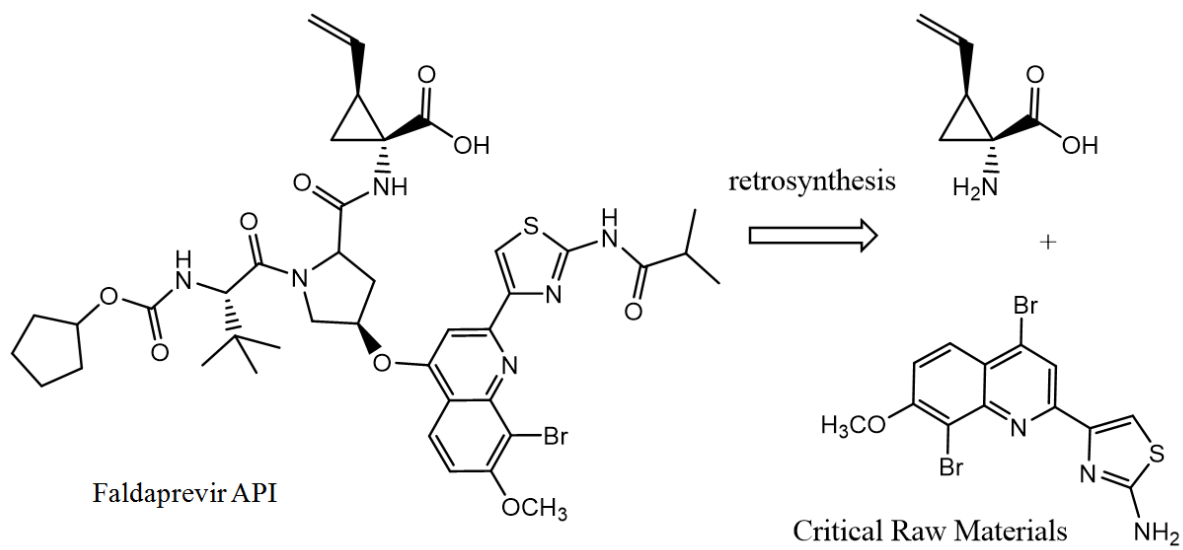


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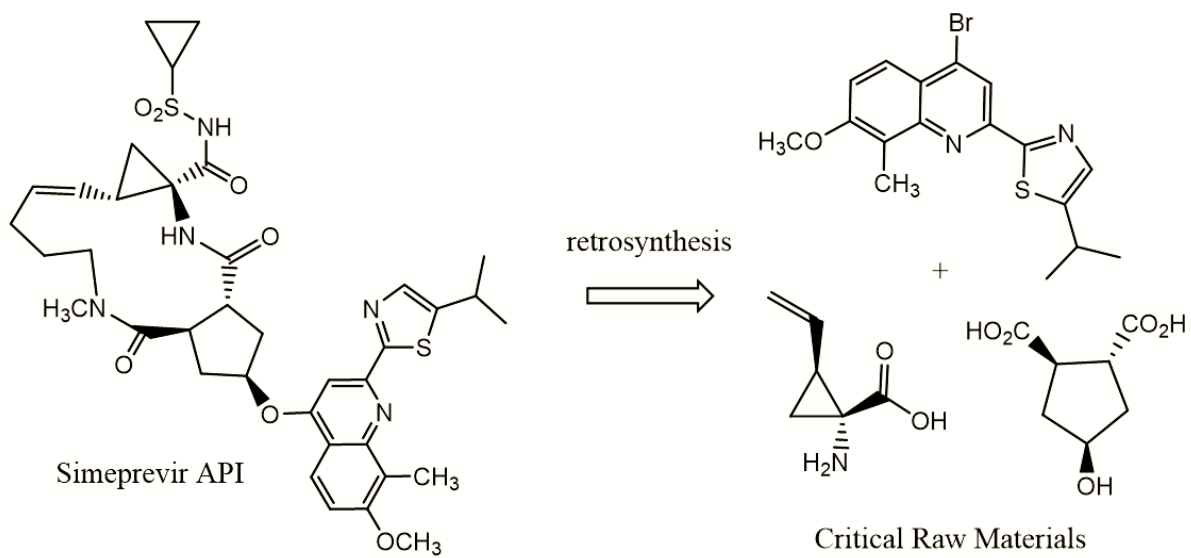


Cost-limiting raw material

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