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Review

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Natural Products As Sources of New Drugs over the 30 Years from 1981 to 2010

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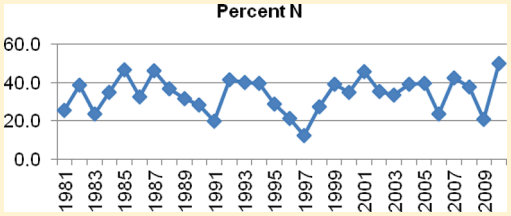
Supporting Information

ABSTRACT: This review is an updated and expanded version of the three prior reviews that were published in this journal in 1997, 2003, and 2007. In the case of all approved therapeutic agents, the time frame has been extended to cover the 30 years from January 1, 1981, to December 31, 2010, for all diseases worldwide, and from 1950 (earliest so far identified) to December 2010 for all approved antitumor drugs worldwide. We have continued to utilize our secondary subdivision of a "natural product mimic" or "NM" to join the original primary divisions and have added a new designation, "natural product botanical" or "NB", to cover those botanical "defined mixtures" that have now been recognized as drug entities by the FDA and similar organizations. From the data presented, the utility of natural products as sources of novel structures, but not necessarily the final drug entity, is still alive and well. Thus, in the area of cancer, over the time frame from around the 1940s to date, of the 175 small molecules, 131, or 74.8%, are other than "S" (synthetic), with 85, or 48.6%, actually being either natural products or directly derived therefrom. In other areas, the influence of natural product structures is quite marked, with, as expected from prior information, the anti-infective area being dependent on natural products and their structures. Although combinatorial chemistry techniques have succeeded as methods of optimizing structures and have been used very successfully in the optimization of many recently approved agents, we are able to identify only one de novo combinatorial compound approved as a drug in this 30-year time frame. We wish to draw the attention of readers to the rapidly evolving recognition that a significant number of natural product drugs/leads are actually produced by microbes and/or microbial interactions with the "host from whence it was isolated", and therefore we consider that this area of natural product research should be expanded significantly.



INTRODUCTION

It has been 14 years since the publication of our first,[1] eight years since the second,[2] and four years[3] since our last full analysis of the sources of new and approved drugs for the treatment of human diseases, although there have been intermediate reports in specific areas such as cancer[4,5] and anti-infectives,[6] together with a more general discussion on natural products as leads to potential drugs.[7] All of these articles demonstrated that natural product and/or natural product structures continued to play a highly significant role in the drug discovery and development process.

That Nature in one guise or another has continued to influence the design of small molecules is shown by inspection of the information given below, where with the advantage of now 30 years of data, the system has been able to be refined. We have eliminated some duplicated entries that crept into the original data sets and have revised a few source designations as newer information has been obtained from diverse sources. In particular, as behooves authors from the National Cancer Institute (NCI), in the specific case of cancer treatments, we have continued to consult the records of the FDA and added comments from investigators who have informed us of compounds that may have been approved in other countries and that were not captured in our earlier searches. As was done previously, the cancer data will be presented as a stand-alone section from the beginning of formal chemotherapy in the very late 1930s or early 1940s to the present, but information from the last 30 years will be included in the data sets used in the overall discussion.

A trend was mentioned in our 2003 review[2] in that, though the development of high-throughput screens based on molecular targets had led to a demand for the generation of large libraries of compounds, the shift away from large combinatorial libraries that was becoming obvious at that time has continued, with the emphasis now being on small focused (100 to ~3000 plus) collections that contain much of the "structural aspects" of natural products. Various names have been given to this process, including "diversity oriented syntheses",[8−12] but we prefer to simply refer to "more natural product-like", in terms of their combinations of heteroatoms and significant numbers of chiral centers within a single molecule,[13] or even "natural product mimics" if they happen to be direct competitive inhibitors of the natural substrate. It should also be pointed out that Lipinski's fifth rule effectively

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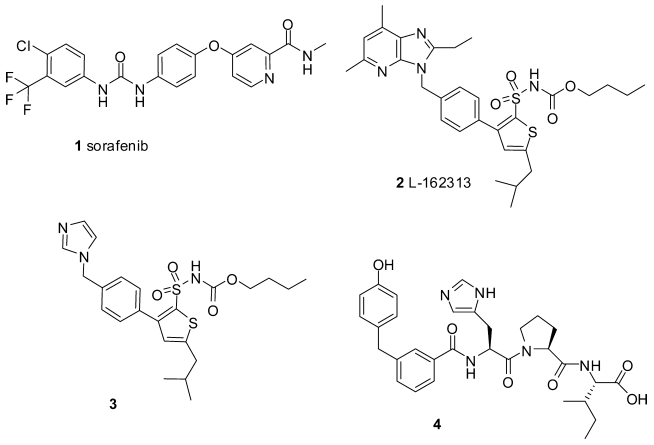
states that the first four rules do not apply to natural products nor to any molecule that is recognized by an active transport system when considering "druggable chemical entities".[14−16] Recent commentaries on the "industrial perspective in regard to drug sources"[17] and high-throughput screening[18] have been published by the GSK group and can be accessed by interested readers.

Although combinatorial chemistry in one or more of its manifestations has now been used as a discovery source for approximately 70% of the time covered by this review, to date, we still can find only one de novo new chemical entity reported in the public domain as resulting from this method of chemical discovery and approved for drug use anywhere. This is the antitumor compound known as sorafenib (Nexavar, **1**) from Bayer, approved by the FDA in 2005 for treatment of renal cell carcinoma, and then in 2007, another approval was given for treatment of hepatocellular carcinoma. It was known during development as BAY-43-9006 and is a multikinase inhibitor, targeting several serine/threonine and receptor tyrosine kinases (RAF kinase, VEGFR-2, VEGFR-3, PDGFR-beta, KIT, and FLT-3). It has been approved in Switzerland, the European Union, and the People's Republic of China, with additional filings in other countries. Currently, it is still in multiple clinical trials in both combination and single-agent therapies, a common practice once a drug is approved for an initial class of cancer treatment.



As mentioned by the present authors and others in prior reviews on this topic, the developmental capability of combinatorial chemistry as a means for structural optimization, once an active skeleton has been identified, is without par. An expected surge in productivity, however, has not materialized. Thus, the number of new active substances (NASs) from our data set, also known as new chemical entities (NCEs), which we consider to encompass all molecules, including biologics and vaccines, hit a 24-year low of 25 in 2004 (although 28% of these were assigned to the "ND" category), leading to a rebound to 54 in 2005, with 24% being "N" or "ND" and 37% being biologics ("B") or vaccines ("V"), as we discuss subsequently. The trend to small numbers of approvals continues to this day, as can be seen by inspection of Figures 2 and 4 (see Discussion section below).

Fortunately, however, research being conducted by groups such as Danishefsky's, Ganesan's, Nicolaou's, Porco's, Quinn's, Schreiber's, Shair's, Tan's, Waldmann's, and Wipf's, together with those of other synthetic chemists, is continuing the modification of active natural product skeletons as leads to novel agents. This was recently exemplified by the groups of Quinn[19] and Danishefsky[20] or the utilization of the "lessons learned" from studying such agents as reported by the groups of Tan[21,22] and Kombarov[23] to name just some of the recent publications. Thus, in due course, the numbers of materials developed by linking Mother Nature to combinatorial synthetic techniques should increase. These aspects, plus the potential contributions from the utilization of genetic analyses of microbes, will be discussed at the end of this review.

Against this backdrop, we now present an updated analysis of the role of natural products in the drug discovery and development process, dating from January 1981 through December 2010. As in our earlier analyses,[1−3] we have consulted the *Annual Reports of Medicinal Chemistry*, in this case from 1984 to 2010,[24−50] and have produced a more comprehensive coverage of the 1981−2010 time frame through addition of data from the publication *Drug News and Perspective*[51−71] and searches of the Prous (now Thomson-Reuter's *Integrity*) database, as well as by including information from individual investigators. As in the last review, biologics data prior to 2005 were updated using information culled from

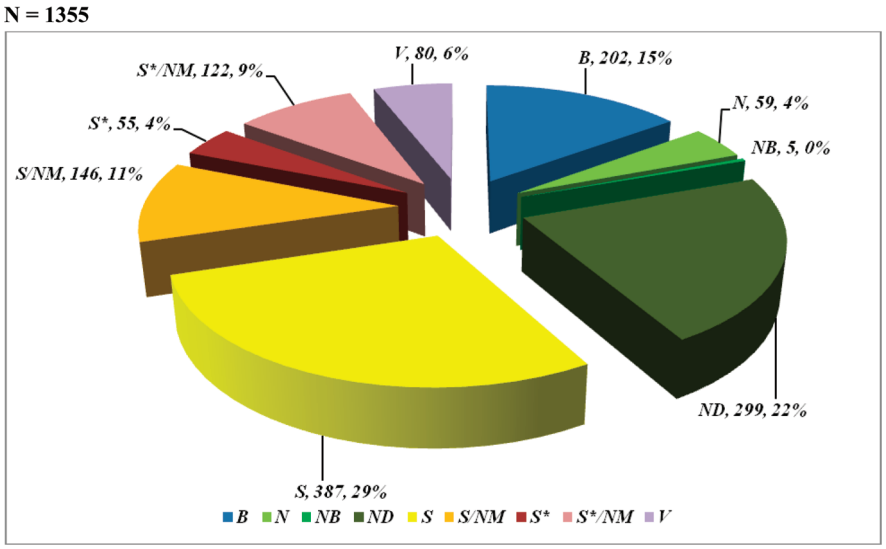


Figure 1. All new approved drugs.

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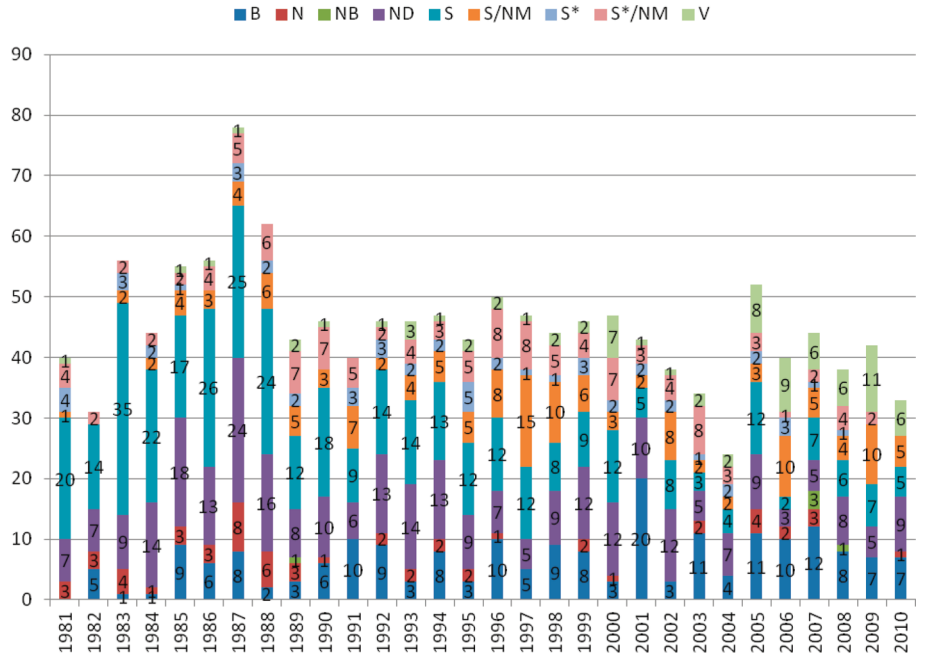

Figure 2. All new approved drugs by source/year.

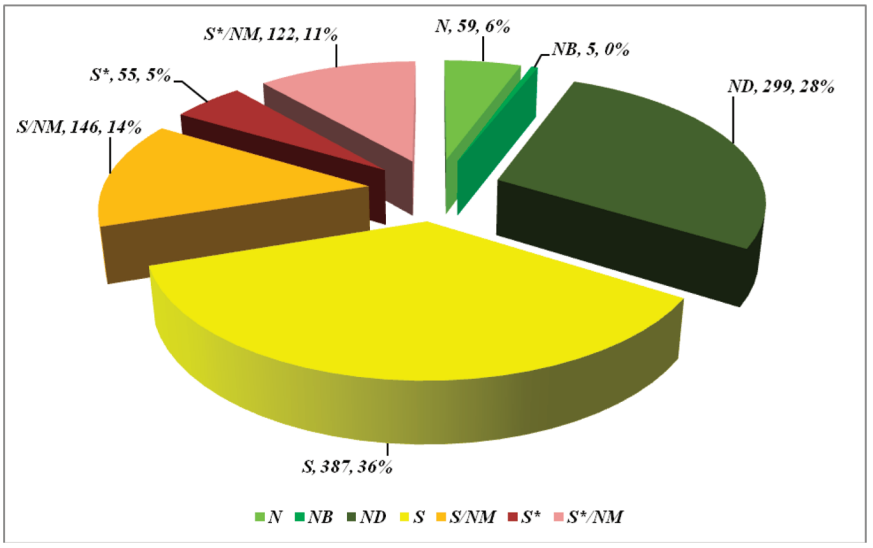

Figure 3. Source of small-molecule approved drugs.

disparate sources that culminated in a 2005 review on biopharmaceutical drugs.[72] We have also attempted to capture vaccine data in the past few years, but this area of the database is not as complete as we would hope.

We have also included relevant references in a condensed form in Tables 2−5 and 8−10. If we were to provide the full citations, the numbers of references cited in the present review would become overwhelming. In these tables, "ARMC ##" refers to the volume of *Annual Reports in Medicinal Chemistry* together with the page on which the structure(s) and commentary can be found. Similarly, "DNP ##" refers to the volume of *Drug News and Perspective* and the corresponding page(s), though this journal has now ceased publication as of the 2010 volume, and an "I ######" is the accession number in the Prous (now Thomson-Reuters, *Integrity*) database. Finally, we have used "Boyd" to refer to a review article[73] on clinical antitumor agents and "M'dale" to refer to *Martindale*[74] with the relevant page noted.

It should be noted that the "year" header in all tables is equivalent to the "year of introduction" of the drug. In a number of cases over the years, there are discrepancies between sources as to the actual year due to differences in definitions. Some reports will use the year of approval (registration by non-USA/FDA organizations), while others will use the first recorded sales. We have generally taken the earliest year in the absence of further information.

RESULTS

As in previous reviews, we have covered only new chemical entities in the present analysis. As mentioned in the earlier reviews, if one reads the FDA and PhRMA Web sites, the numbers of NDA approvals are in the high ten to low hundred numbers for the past few years. If, however, combinations of

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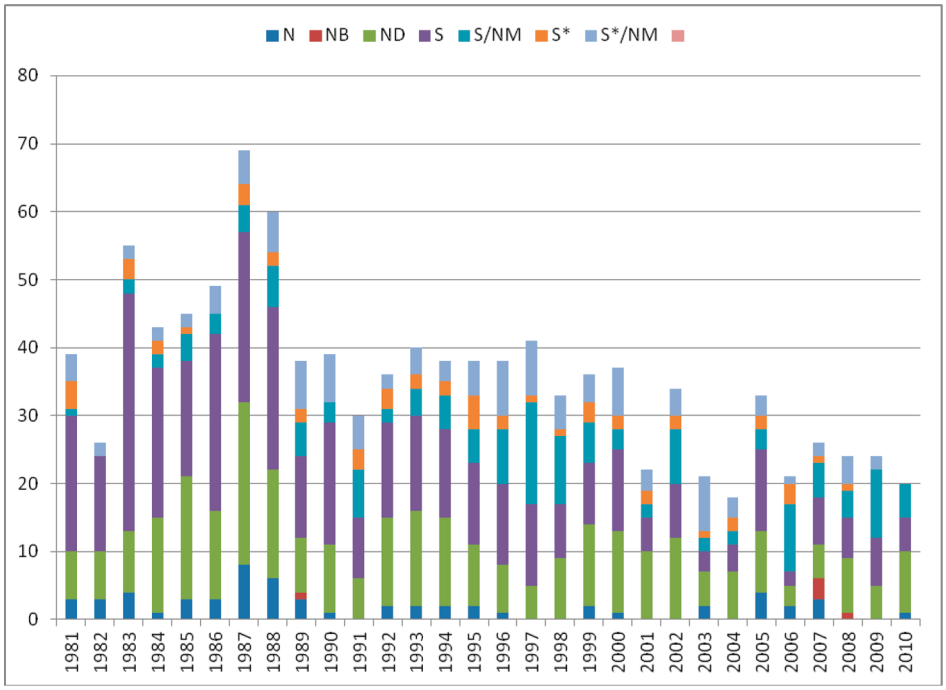

Figure 4. Sources of small molecule NCEs by source/year.

Table 1. New Chemical Entities and Medical Indications by Source of Compound 01/01/1981 to 12/31/2010[a]

indication	total	B	N	NB	ND	S	S/NM	S*	S*/NM	V
COPD	4						1		3	
analgesic	17		1			11	3	2		
anesthetic	5					5				
anti-Alzheimer	4		1				3			
anti-Parkinsonian	12				2	1	5		4	
antiallergic	17		1	1	4	11				
antianginal	5					5				
antiarrhythmic	17		1			14			2	
antiarthritic	17	6	1		1	3	6			
antiasthmatic	14	1			3	2	6		2	
antibacterial	118		10		67	26			1	14
anticancer	128	24	11	1	32	20	16	11	8	5
anticoagulant	19	5			13			1		
antidepressant	23					7	14		2	
antidiabetic	37	18	1		5	4	8	1		
antiemetic	11					1	2		8	
antiepileptic	15				2	9		2	2	
antifungal	29	1			3	22	3			
antiglaucoma	14				5		5	1	3	
antihistamine	13					13				
antihyperprolactinemia	4				4					
antihypertensive	79				2	28	14	2	33	
anti-inflammatory	51	1			13	37				
antimigraine	10					2	1		7	
antiobesity	4				1		3			
antiparasitic	14		2		5	4		2		1
antipsoriatic	9	3		1	3			1	1	
antipsychotic	10					3	5		2	
antithrombotic	29	13	1		5	2	6		2	
antiulcer	34	1	1		12	20				
antiviral	110	14			4	9	2	23	10	48
anxiolytic	10					8	2			
benign prostatic hypertrophy	4		1		1	1	1			

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Table 1. continued

indication	total	B	N	NB	ND	S	S/NM	S*	S*/NM	V
bronchodilator	8				2				6	
calcium metabolism	20				8	9	3			
cardiotonic	13				3	2	3		5	
chelator	4					4				
contraception	9				8		1			
diuretic	6					4	2			
erythropoiesis	5	5								
gastroprokinetic	4					1	2		1	
hematopoiesis	6	6								
hemophilia	12	12								
hormone	22	12			10					
hormone replacement therapy	8				8					
hypnotic	12					12				
hypocholesterolemic	13		4		1	2	1		5	
hypolipidemic	8		1			7				
immunomodulator	4	2	1		1					
immunostimulant	11	5	3		2	1				
immunosuppressant	12	4	5		3					
irritable bowel syndrome	4					1			3	
male sexual dysfunction	4								4	
multiple sclerosis	6	3			1	1		1		
muscle relaxant	10				4	2	1	3		
neuroleptic	9					1	6		2	
nootropic	8				3	5				
osteoporosis	5	3			1	1				
platelet aggregation inhibitor	4				3		1			
respiratory distress syndrome	6	3	1			1	1			
urinary incontinence	5					2	3			
vulnerary	5	2			2	1				
Grand Total	1130	144	47	3	247	325	130	50	116	68

[a]Diseases where ≤3 drugs approved 1981−2010; 225 drugs fall into this category and are subdivided as follows: B, 58; N, 12; NB, 2; ND, 52; S, 62, S/NM. 16; S*, 5; S*/NM, 6; V, 12. The diseases covered the following; 5 α-reductase inhibitor, ADHD, CAPS, CHF, CNS stimulant, Crohn's disease, DVT, Fabry's disease, Gaucher's disease, Hunter syndrome, Japanese encephalitis, Lambert-Eaton myasthenic syndrome, Lyme disease, MI acute, MMRC, PAH, PCP/toxoplasmosis, PNH, Pompe's disease, Turner syndrome, abortifacient, acromelagy, actinic keratoses, adjuvant/colorectal cancer, alcohol deterrent, allergic rhinitis, anabolic metabolism, analeptic, anemia, anti sickle cell anemia, antismoking, antiacne, antiatherosclerotic, anticonvulsant, antidiarrheal, antidote, antiemphysemic, antihyperuricemia, antihypotensive, antinarcolepsy, antinarcotic, antinauseant, antiperistaltic, antipneumococcal, antiprogestogenic, antirheumatic, antisecretory, antisepsis, antiseptic, antispasmodic, antispastic, antitussive, antityrosinaemia, antixerostomia, atrial fibrillation, benzodiazepine antagonist, β-lactamase inhibitor, blepharospasm, bone disorders, bone morphogenesis, bowel evacuant, cardioprotective, cardiovascular disease, cartilage disorders, cervical dystonia, choleretic, chronic idiopathic constipation, cognition enhancer, congestive heart failure, constipation, cystic fibrosis, cytoprotective, dementia (Alzheimer's), diabetic foot ulcers, diabetic neuropathies, digoxin toxicity, dpt, dry eye syndrome, dyslipidemia, dysuria, endometriosis, enzyme, expectorant, fertility inducer, gastroprotectant, genital warts, hematological, hemorrhage, hemostasis, hemostatic, hepatoprotectant, hereditary angioedema, homocystinuria, hyperammonemia, hyperparathyroidism, hyperphenylalaninemia, hyperphosphatemia, hyperuricemia, hypoammonuric, hypocalciuric, hypogonadism, hyponatremia, idiopathic pulmonary fibrosis, idiopathic thrombocytopenia, immediate allergy, infertility (female), inflammatory bowel disease, insomnia, joint lubricant, lipoprotein disorders, macular degeneration, mucolytic, mucopolysaccharidosis, mucositis, myleodysplasia, narcolepsy, nasal decongestant, neuropathic pain, neuroprotective, ocular inflammation, opiate detoxification, osteoarthritis, overactive bladder, ovulation, pancreatic disorders, pancreatitis, pertussis, photosensitizer, pituitary disorders, porphyria, premature birth, premature ejaculation, progestogen, psychostimulant, pulmonary arterial hypertension, purpura fulminans, rattlesnake antivenom, reproduction, restenosis, schizophrenia, sclerosant, secondary hyperthryoidism, sedative, skin photodamage, strabismus, subarachnoid hemorrhage, thrombocytopenia, GH deficiency, ulcerative colitis, urea cycle disorders, uremic pruritis, urolithiasis, vaccinia complications, varicella (chicken pox), vasodilator, vasodilator (cerebral), vasodilator (coronary), vasoprotective, venous thromboembolism.

older drugs and old drugs with new indications and/or improved delivery systems are removed, then the number of true NCEs has ranged between the 20s to just over 50 per year since 1989. If one now removes biologicals and vaccines, thus noting only "small molecules", then the figures show that over the same time frame the numbers have been close to 40 for most of the 1989 to 2000 time frame, dropping to 20 or less from 2001 to 2010 with the exception of 2002 and 2004, when the figures climbed above 30 (cf. Figures 2 and 4).

For the first time, now with 30 years of data to analyze, it was decided to add two other graphs to the listings, of which one might be of significant interest to the natural products community. In Figure 5 the percentages of approved NCEs have been plotted per year from 1981 to 2010, where the designation is basically an "N" or a subdivision ("NB" or "ND") with the total numbers of small molecules approved by year as a point chart in Figure 6. Thus, we have deliberately not included any designations that could be considered as "inspired by a natural product structure", although from the data provided

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either in the tables or from the Supporting Information any reader who so desires may calculate their own particular variation(s) in Figure 5.

As in our earlier reviews,[1−3] the data have been analyzed in terms of numbers and classified according to their origin using the previous major categories and their subdivisions.

Major Categories of Sources. The major categories used are as follows:

"B" Biological; usually a large (>45 residues) peptide or protein either isolated from an organism/cell line or produced by biotechnological means in a surrogate host.
"N" Natural product.
"NB" Natural product "Botanical" (in general these have been recently approved).
"ND" Derived from a natural product and is usually a semisynthetic modification.
"S" Totally synthetic drug, often found by random screening/modification of an existing agent.
"S*" Made by total synthesis, but the pharmacophore is/was from a natural product.
"V" Vaccine.

Subcategory. "NM" Natural Product Mimic (see rationale and examples below). (For amplification of the rationales used for categorizing using the above subdivisions, the reader should consult the earlier reviews.[1−3])

In the field of anticancer therapy, the advent in 2001 of Gleevec, a protein tyrosine kinase inhibitor, was justly heralded as a breakthrough in the treatment of leukemia. This compound was classified as an "/NM" on the basis of its competitive displacement of the natural substrate, ATP, in which the intracellular concentrations can approach 5 mM. We have continued to classify PTK and other kinase inhibitors that are approved as drugs under the "/NM" category for exactly the same reasons as elaborated in the 2003 review[2] and have continued to extend it to cover other direct inhibitors/antagonists of the natural substrate/receptor interaction whether obtained by direct experiment or by in silico studies followed by direct assay in the relevant system.

Similarly, a number of new peptidic drug entities, although formally synthetic in nature, are simply produced by synthetic methods rather than by the use of fermentation or extraction. In some cases, an end group might have been changed for ease of recovery. In addition, a number of compounds produced totally by synthesis are in fact isosteres of the peptidic substrate and are thus "natural product mimics" in the truest sense of the term. For further information on this area, interested readers should consult the excellent earlier review by Hruby,[75] his 2009 "Perspective" review,[76] and very recent work in the same area by Audie and Boyd[77] and VanHee et al.[78] in order to fully appreciate the potential of such (bio)chemistry.

As an example of what can be found by studies on relatively simple peptidomimics of the angiotensin II structure, the paper of Wan et al.[79] demonstrating the modification of the known but nonselective AT_1/AT_2 agonist L-162313 (**2**, itself related to the sartans) into the highly selective AT_2 agonist **3** (a peptidomimetic structure) led to the identification of short pseudopeptides exemplified by **4**, which is equipotent (binding affinity = 500 pM) to angiotensin II and has a better than 20 000-fold selectivity versus AT_1, whereas angiotensin II has only a 5-fold binding selectivity in the same assay,[80] as reported in our 2007 review. The chemistry leading to these compounds was reported in 2007 in greater detail by Georgsson et al.,[81] with a thorough discussion of the role of AT_2 receptors in a multiplicity of disease states being published in 2008.[82] To date, we have not found any clinical trials reported on these materials.

In the area of modifications of natural products by combinatorial methods to produce entirely different compounds that may bear little if any resemblance to the original, but are legitimately assignable to the "/NM" category, citations are given in previous reviews.[8,83−90] In addition, one should consult the reports from Waldmann's group[91,92] and those by Ganesan,[93,94] Shang and Tan,[95] Bauer et al.,[21] Constantino and Barlocco,[96] Bade et al.,[97] and Violette et al.,[98] demonstrating the use of privileged structures as a source of molecular skeletons around which one may build libraries. Another paper of interest in this regard is the editorial by Macarron from GSK,[15] as this may be the first time where data from industry on the results of HTS screens of combichem libraries versus potential targets were reported with a discussion of lead discovery rates. In this paper, Macarron re-emphasizes the fifth Lipinski rule, which is often ignored: "natural products do not obey the other four".

Overview of Results. The data we have analyzed in a variety of ways are presented as a series of bar graphs and pie charts and two major tables in order to establish the overall picture and then are further subdivided into some major therapeutic areas using a tabular format. The time frame covered is the 30 years from 01/01/1981 to 12/31/2010:

New approved drugs: With all source categories (Figure 1)
New approved drugs: By source/year (Figure 2)
Sources of all NCEs: Where four or more drugs were approved per medical indication (Table 1), with listings of diseases with ≤3 approved drugs
Sources of small-molecule NCEs: All subdivisions (Figure 3)
Sources of small-molecule NCEs: By source/year (Figure 4)
Percent N/NB/ND: By year (Figure 5)
Total small molecules: By year (Figure 6)
Antibacterial drugs: Generic and trade names, year, reference, and source (Table 2)
Antifungal drugs: Generic and trade names, year, reference, and source (Table 3)
Antiviral drugs: Generic and trade names, year, reference, and source (Table 4)
Antiparasitic drugs: Generic and trade names, year, reference, and source (Table 5)
Anti-infective drugs: All molecules, source, and numbers (Table 6)
Anti-infective drugs: Small molecules, source, and numbers (Table 7)
Anticancer drugs: Generic and trade names, year, reference, and source (Table 8; Figure 7)
All anticancer drugs (very late 1930s−12/2010): Generic and trade names, year, reference, and source (Table 9; Figures 8, 9)
Antidiabetic drugs: Generic and trade names, year, reference, and source (Table 10)

The extensive data sets shown in the figures and tables referred to above highlight the continuing role that natural products and structures derived from or related to natural products from all sources have played, and continue to play, in the development of the current therapeutic armamentarium of

Table 2. Antibacterial Drugs from 01/01/1981 to 12/31/2010 Organized Alphabetically by Generic Name within Source

generic name	trade name	year introduced	volume	page	source
carumonam	Amasulin	1988	ARMC 24	298	N
daptomycin	Cubicin	2003	ARMC 39	347	N
fosfomycin trometamol	Monuril	1988	I 112334		N
isepamicin	Isepacin	1988	ARMC 24	305	N
micronomicin sulfate	Sagamicin	1982	P091082		N
miokamycin	Miocamycin	1985	ARMC 21	329	N
mupirocin	Bactroban	1985	ARMC 21	330	N
netilimicin sulfate	Netromicine	1981	I 070366		N
RV-11	Zalig	1989	ARMC 25	318	N
teicoplanin	Targocid	1988	ARMC 24	311	N
apalcillin sodium	Lumota	1982	I 091130		ND
arbekacin	Habekacin	1990	ARMC 26	298	ND
aspoxicillin	Doyle	1987	ARMC 23	328	ND
astromycin sulfate	Fortimicin	1985	ARMC 21	324	ND
azithromycin	Sunamed	1988	ARMC 24	298	ND
aztreonam	Azactam	1984	ARMC 20	315	ND
biapenem	Omegacin	2002	ARMC 38	351	ND
cefbuperazone sodium	Tomiporan	1985	ARMC 21	325	ND
cefcapene pivoxil	Flomox	1997	ARMC 33	330	ND
cefdinir	Cefzon	1991	ARMC 27	323	ND
cefditoren pivoxil	Meiact	1994	ARMC 30	297	ND
cefepime	Maxipime	1993	ARMC 29	334	ND
cefetamet pivoxil HCl	Globocef	1992	ARMC 28	327	ND
cefixime	Cefspan	1987	ARMC 23	329	ND
cefmenoxime HCl	Tacef	1983	ARMC 19	316	ND
cefminox sodium	Meicelin	1987	ARMC 23	330	ND
cefodizime sodium	Neucef	1990	ARMC 26	300	ND
cefonicid sodium	Monocid	1984	ARMC 20	316	ND
cefoperazone sodium	Cefobis	1981	I 127130		ND
ceforanide	Precef	1984	ARMC 20	317	ND
cefoselis	Wincef	1998	ARMC 34	319	ND
cefotetan disodium	Yamatetan	1984	ARMC 20	317	ND
cefotiam HCl	Pansporin	1981	I 091106		ND
cefozopran HCl	Firstcin	1995	ARMC 31	339	ND
cefpimizole	Ajicef	1987	ARMC 23	330	ND
cefpiramide sodium	Sepatren	1985	ARMC 21	325	ND
cefpirome sulfate	Cefrom	1992	ARMC 28	328	ND
cefpodoxime proxetil	Banan	1989	ARMC 25	310	ND
cefprozil	Cefzil	1992	ARMC 28	328	ND
cefsoludin sodium	Takesulin	1981	I 091108		ND
ceftazidime	Fortam	1983	ARMC 19	316	ND
cefteram pivoxil	Tomiron	1987	ARMC 23	330	ND
ceftibuten	Seftem	1992	ARMC 28	329	ND
ceftizoxime sodium	Epocelin	1982	I 070260		ND
ceftobiprole medocaril	Zeftera	2008	ARMC 44	589	ND
ceftriaxone sodium	Rocephin	1982	I 091136		ND
cefuroxime axetil	Zinnat	1987	ARMC 23	331	ND
cefuzonam sodium	Cosmosin	1987	ARMC 23	331	ND
clarithromycin	Klaricid	1990	ARMC 26	302	ND
dalfopristin	Synercid	1999	ARMC 35	338	ND
dirithromycin	Nortron	1993	ARMC 29	336	ND
doripenem	Finibax	2005	DNP 19	42	ND
ertapenem sodium	Invanz	2002	ARMC 38	353	ND
erythromycin acistrate	Erasis	1988	ARMC 24	301	ND
flomoxef sodium	Flumarin	1988	ARMC 24	302	ND
flurithromycin ethylsuccinate	Ritro	1997	ARMC 33	333	ND
fropenam	Farom	1997	ARMC 33	334	ND
imipenem/cilastatin	Zienam	1985	ARMC 21	328	ND
lenampicillin HCI	Varacillin	1987	ARMC 23	336	ND
loracarbef	Lorabid	1992	ARMC 28	333	ND
meropenem	Merrem	1994	ARMC 30	303	ND

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Table 2. continued

generic name	trade name	year introduced	volume	page	source
moxalactam disodium	Shiomarin	1982	I 070301		ND
panipenem/betamipron	Carbenin	1994	ARMC 30	305	ND
quinupristin	Synercid	1999	ARMC 35	338	ND
retapamulin	Altabax	2007	ARMC 43	486	ND
rifabutin	Mycobutin	1992	ARMC 28	335	ND
rifamixin	Normix	1987	ARMC 23	341	ND
rifapentine	Rifampin	1988	ARMC 24	310	ND
rifaximin	Rifacol	1985	ARMC 21	332	ND
rokitamycin	Ricamycin	1986	ARMC 22	325	ND
roxithromycin	Rulid	1987	ARMC 23	342	ND
sultamycillin tosylate	Unasyn	1987	ARMC 23	343	ND
tazobactam sodium	Tazocillin	1992	ARMC 28	336	ND
telavancin HCl	Vibativ	2009	DNP 23	15	ND
telithromycin	Ketek	2001	DNP 15	35	ND
temocillin disodium	Temopen	1984	ARMC 20	323	ND
tigecycline	Tygacil	2005	DNP 19	42	ND
balafloxacin	Q-Roxin	2002	ARMC 38	351	S
besifloxacin	Besivance	2009	DNP 23	20	S
ciprofloxacin	Ciprobay	1986	ARMC 22	318	S
enoxacin	Flumark	1986	ARMC 22	320	S
fleroxacin	Quinodis	1992	ARMC 28	331	S
garenoxacin	Geninax	2007	ARMC 43	471	S
gatilfloxacin	Tequin	1999	ARMC 35	340	S
gemifloxacin mesilate	Factive	2003	ARMC 40	458	S
grepafloxacin	Vaxor	1997	DNP 11	23	S
levofloxacin	Floxacin	1993	ARMC 29	340	S
linezolid	Zyvox	2000	DNP 14	21	S
lomefloxacin	Uniquin	1989	ARMC 25	315	S
moxifloxacin HCl	Avelox	1999	ARMC 35	343	S
nadifloxacin	Acuatim	1993	ARMC 29	340	S
norfloxacin	Noroxin	1983	ARMC 19	322	S
ofloxacin	Tarivid	1985	ARMC 21	331	S
pazufloxacin	Pasil	2002	ARMC 38	364	S
pefloxacin mesylate	Perflacine	1985	ARMC 21	331	S
prulifloxacin	Sword	2002	ARMC 38	366	S
rufloxacin hydrochloride	Qari	1992	ARMC 28	335	S
sitafloxacin hydrate	Gracevit	2008	DNP 22	15	S
sparfloxacin	Spara	1993	ARMC 29	345	S
taurolidine	Taurolin	1988	I 107771		S
temafloxacin hydrochloride	Temac	1991	ARMC 27	334	S
tosufloxacin	Ozex	1990	ARMC 26	310	S
trovafloxacin mesylate	Trovan	1998	ARMC 34	332	S
brodimoprin	Hyprim	1993	ARMC 29	333	S*/NM
ACWY meningoccal PS vaccine	Mencevax	1981	I 420128		V
DTPw-HepB-Hib	Quinvaxem	2006	DNP 20	26	V
H. influenzae b vaccine	Hibtitek	1989	DNP 03	24	V
H. influenzae b vaccine	Prohibit	1989	DNP 03	24	V
MCV-4	Menactra	2005	DNP 19	43	V
menACWY-CRM	Menveo	2010	I 341212		V
meningitis b vaccine	MeNZB	2004	DNP 18	29	V
meningococcal vaccine	Menigetec	1999	DNP 14	22	V
meningococcal vaccine	NeisVac-C	2000	DNP 14	22	V
meningococcal vaccine	Menjugate	2000	DNP 14	22	V
oral cholera vaccine	Orochol	1994	DNP 08	30	V
pneumococcal vaccine	Prevnar	2000	DNP 14	22	V
PsA-TT	MenAfriVac	2010	I 437718		V
vi polysaccharide typhoid vaccine	Typherix	1998	DNP 12	35	V

the physician. Inspection of the data shows the continued important role for natural products in spite of the current greatly reduced level of natural products-based drug discovery programs in major pharmaceutical houses.

Table 3. Antifungal Drugs from 01/01/1981 to 12/31/2010 Organized Alphabetically by Generic Name within Source

generic name	trade name	year introduced	volume	page	source
interferon γ-n1	OGamma100	1996	DNP 10	13	B
anidulafungin	Eraxis	2006	DNP 20	24	ND
caspofungin acetate	Cancidas	2001	DNP 15	36	ND
micafungin sodium	Fungard	2002	ARMC 38	360	ND
amorolfine hydrochloride	Loceryl	1991	ARMC 27	322	S
butoconazole	Femstat	1986	ARMC 22	318	S
ciclopirox olamine	Loprox	1982	I 070449		S
cloconazole HCl	Pilzcin	1986	ARMC 22	318	S
eberconazole	Ebernet	2005	DNP 19	42	S
fenticonazole nitrate	Lomexin	1987	ARMC 23	334	S
fluconazole	Diflucan	1988	ARMC 24	303	S
flutrimazole	Micetal	1995	ARMC 31	343	S
fosfluconazole	Prodif	2003	DNP 17	49	S
itraconazole	Sporanox	1988	ARMC 24	305	S
ketoconazole	Nizoral	1981	I 116505		S
lanoconazole	Astat	1994	ARMC 30	302	S
luliconazole	Lulicon	2005	DNP 19	42	S
naftifine HCl	Exoderil	1984	ARMC 20	321	S
neticonazole HCl	Atolant	1993	ARMC 29	341	S
oxiconazole nitrate	Oceral	1983	ARMC 19	322	S
posaconazole	Noxafil	2005	DNP 19	42	S
sertaconazole nitrate	Dermofix	1992	ARMC 28	336	S
sulconazole nitrate	Exelderm	1985	ARMC 21	332	S
terconazole	Gyno-Terazol	1983	ARMC 19	324	S
tioconazole	Trosyl	1983	ARMC 19	324	S
voriconazole	Vfend	2002	ARMC 38	370	S
butenafine hydrochloride	Mentax	1992	ARMC 28	327	S/NM
liranaftate	Zefnart	2000	DNP 14	21	S/NM
terbinafine hydrochloride	Lamisil	1991	ARMC 27	334	S/NM

Inspection of the rate of NCE approvals as shown in Figures 2 and 4−6 demonstrates that, even in 2010, the natural products field is still producing or is involved in ca. 50% of all small molecules in the years 2000−2010. This is readily demonstrated in Figures 5 and 6, where the percentage of just the "N" linked materials is shown, with figures ranging from a low of 20.8% in 2009 to a high of 50% in 2010, with the mean and standard deviation for those 11 years being 36.5 ± 8.6, without including any of the natural product-inspired classifications (S*, S*/NM, and S/NM). What is quite fascinating is that in 2010 fully half of the 20 approved small-molecule NCEs fell into the "N" categories, including the majority of the antitumor agents (cf. Tables 2−4; 8).

As was shown in the 2007 review, a significant number of all NCEs still fall into the categories of biological ("B") or vaccines ("V"), with 282 of 1355 (or 20.8%) over the full 30-year period, and it is to be admitted that not all of the vaccines approved in these 30 years have been identified, although in the last 10 or 11 years probably a great majority have been captured. Thus, the proportion of approved vaccines may well be higher over the longer time frame. Inspection of Figure 2 shows the significant proportion that these two categories hold in the number of approved drugs from 2000, where, in some years, these categories accounted for ca. 50% of all approvals. If the three "N" categories are included, then the proportions of nonsynthetics are even higher for these years. This is so in spite of many years of work by the pharmaceutical industry devoted to high-throughput screening of predominately combinatorial chemistry products, and this time period should have provided a sufficient time span for combinatorial chemistry work from the late 1980s onward to have produced a number of approved NCEs.

Overall, of the 1355 NCEs covering all diseases/countries/sources in the years 01/1981−12/2010, and using the "NM" classifications introduced in our 2003 review,[2] 29% were synthetic in origin, thus demonstrating the influence of "other than formal synthetics" on drug discovery and approval (Figure 1). In the 2007 review, the corresponding figure was 30%.[3]

Inspection of Table 1 demonstrates that, overall, the major disease areas that have been investigated (in terms of numbers of drugs approved) in the pharmaceutical industry continue to be infectious diseases (microbial, parasitic, and viral), cancer, hypertension, and inflammation, all with over 50 approved drug therapies. It should be noted, however, that numbers of approved drugs/disease do not correlate with the "value" as measured by sales. For example, the best selling drug of all is atorvastatin (Lipitor), a hypocholesterolemic descended directly from a microbial natural product, which sold over $11 billion in 2004, and, if one includes sales by Pfizer and Astellas Pharma over the 2004 to 2010 time frames, sales have hovered at $12−14 billion depending upon the year. The first U.S. patent for this drug expired in March 2010, and Ranbaxy, the Indian generics company, launched the generic version in the U.S. in December 2011, following FDA approval on the last day of the Pfizer patent, November 30, 2011.

The major category by far is that of anti-infectives including antiviral vaccines, with 270 (23.9%) of the total (1130 for indications ≥ 4) falling into this one major human disease area.

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Table 4. Antiviral Drugs from 01.01.81 to 12.31.10 Organized Alphabetically by Generic Name within Source

generic name	trade name	year introduced	volume	page	source
interferon α	Alfaferone	1987	I 215443		B
interferon α-n3	Alferon N	1990	DNP 04	104	B
interferon β	Frone	1985	I115091		B
immunoglobulin intravenous	Gammagard Liquid	2005	I 231564		B
interferon alfacon-1	Infergen	1997	ARMC 33	336	B
IGIV-HB	Niuliva	2009	DNP 23	16	B
	Oralgen	2007	I 415378		B
peginterferon α-2a	Pegasys	2001	DNP 15	34	B
peginterferon α-2b	Pegintron	2000	DNP 14	18	B
resp syncytial virus IG	RespiGam	1996	DNP 10	11	B
palivizumab	Synagis	1998	DNP 12	33	B
interferon α-2b	Viraferon	1985	I 165805		B
interferon α-n1	Wellferon	1986	I 125561		B
thymalfasin	Zadaxin	1996	DNP 10	11	B
enfuvirtide	Fuzeon	2003	ARMC 39	350	ND
laninamivir octanoate	Inavir	2010	I 340894		ND
peramivir	PeramiFlu	2010	I 273549		ND
zanamivir	Relenza	1999	ARMC 35	352	ND
imiquimod	Aldara	1997	ARMC 33	335	S
maraviroc	Celsentri	2007	ARMC 43	478	S
foscarnet sodium	Foscavir	1989	ARMC 25	313	S
raltegravir potassium	Isentress	2007	ARMC 43	484	S
delavirdine mesylate	Rescriptor	1997	ARMC 33	331	S
rimantadine HCI	Roflual	1987	ARMC 23	342	S
propagermanium	Serosion	1994	ARMC 30	308	S
efavirenz	Sustiva	1998	ARMC 34	321	S
nevirapine	Viramune	1996	ARMC 32	313	S
darunavir	Prezista	2006	DNP 20	25	S/NM
oseltamivir	Tamiflu	1999	ARMC 35	346	S/NM
entecavir	Baraclude	2005	DNP 19	39	S*
ganciclovir	Cymevene	1988	ARMC 24	303	S*
emtricitabine	Emtriva	2003	ARMC 39	350	S*
lamivudine	Epivir	1995	ARMC 31	345	S*
famciclovir	Famvir	1994	ARMC 30	300	S*
adefovir dipivoxil	Hepsera	2002	ARMC 38	348	S*
epervudine	Hevizos	1988	I 157373		S*
zalcitabine	Hivid	1992	ARMC 28	338	S*
inosine pranobex	Imunovir	1981	I 277341		S*
etravirine	Intelence	2008	DNP 22	15	S*
clevudine	Levovir	2007	ARMC 43	466	S*
zidovudine	Retrovir	1987	ARMC 23	345	S*
telbividine	Sebivo	2006	DNP 20	22	S*
sorivudine	Usevir	1993	ARMC 29	345	S*
valganciclovir	Valcyte	2001	DNP 15	36	S*
valaciclovir HCl	Valtrex	1995	ARMC 31	352	S*
penciclovir	Vectavir	1996	ARMC 32	314	S*
didanosine	Videx	1991	ARMC 27	326	S*
tenofovir disoproxil fumarate	Viread	2001	DNP 15	37	S*
cidofovir	Vistide	1996	ARMC 32	306	S*
stavudine	Zerit	1994	ARMC 30	311	S*
abacavir sulfate	Ziagen	1999	ARMC 35	333	S*
acyclovir	Zovirax	1981	I 091119		S*
amprenavir	Agenerase	1999	ARMC 35	334	S*/NM
tipranavir	Aptivus	2005	DNP 19	42	S*/NM
indinavir sulfate	Crixivan	1996	ARMC 32	310	S*/NM
saquinavir mesylate	Invirase	1995	ARMC 31	349	S*/NM
lopinavir	Kaletra	2000	ARMC 36	310	S*/NM
fosamprenevir	Lexiva	2003	ARMC 39	353	S*/NM
ritonavir	Norvir	1996	ARMC 32	317	S*/NM
atazanavir	Reyataz	2003	ARMC 39	342	S*/NM
neflinavir mesylate	Viracept	1997	ARMC 33	340	S*/NM

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Table 4. continued

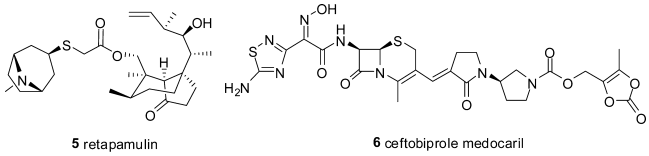
generic name	trade name	year introduced	volume	page	source
fomivirsen sodium	Vitravene	1998	ARMC 34	323	S*/NM
H5N1 avian flu vaccine		2007	I 440743		V
influenza A(H1N1) monovalent		2010	I 678265		V
	ACAM-2000	2007	I 328985		V
influenza virus vaccine	Afluria	2007	I 449226		V
hepatitis A vaccine	Aimmugen	1995	DNP 09	23	V
hepatitis A and B vaccine	Ambirix	2003	I 334416		V
split influenza vaccine	Anflu	2006	DNP 20	26	V
inact hepatitis A vaccine	Avaxim	1996	DNP 10	12	V
hepatitis B vaccine	Biken-HB	1993	DNP 07	31	V
	Bilive	2005	DNP 19	43	V
hepatitis B vaccine	Bio-Hep B	2000	DNP 14	22	V
	Celtura	2009	DNP 23	17	V
	Celvapan	2009	DNP 23	17	V
	Daronix	2007	I 427024		V
hepatitis B vaccine	Engerix B	1987	I 137797		V
rubella vaccine	Ervevax	1985	I 115078		V
hepatitis B vaccine	Fendrix	2005	DNP 19	43	V
influenza virus (live)	FluMist	2003	ARMC 39	353	V
	Fluval P	2009	DNP 23	17	V
	Focetria	2009	DNP 23	17	V
hpv vaccine	Gardasil	2006	DNP 20	26	V
	Grippol Neo	2009	DNP 23	16	V
hepatitis A vaccine	Havrix	1992	DNP 06	99	V
hepatitis B vaccine	Hepacure	2000	DNP 14	22	V
anti-hep B immunoglobulin	HepaGam B	2006	DNP 20	27	V
HN-VAC	HNVAC	2010	I 684608		V
influenza vaccine	Invivac	2004	I 391186		V
MR vaccine	Mearubik	2005	DNP 19	44	V
hepatitis B vaccine	Meinyu	1997	DNP 11	24	V
attenuated chicken pox vaccine	Merieux Varicella Vaccine	1993	DNP 07	31	V
	Optaflu	2007	I 410266		V
influenza vaccine	Optaflu	2008	DNP 22	16	V
	Pandremix	2009	DNP 23	17	V
	Panenza	2009	DNP 23	17	V
	Panflu	2008	DNP 22	16	V
VCIV	PreFluCel	2010	I 444826		V
GSK-1562902A	Prepandrix	2008	DNP 22	16	V
antirabies vaccine	Rabirix	2006	DNP 20	27	V
rotavirus vaccine	Rotarix	2005	DNP 18	29	V
rotavirus vaccine	Rota-Shield	1998	DNP 12	35	V
rotavirus vaccine	Rotateq	2006	DNP 20	26	V
rec hepatitis B vaccine	Supervax	2006	DNP 20	27	V
hepatitis A vaccine	Vaqta	1996	DNP 10	11	V
varicella virus vaccine	Varivax	1995	DNP 09	25	V
	VariZIG	2005	I 230590		V
	Vaxiflu-S	2010	I 698015		V
zoster vaccine live	Zostavax	2006	DNP 20	26	V

On further analysis (Tables 6 and 7), the influence of biologicals and vaccines in this disease complex is such that only 22.6% are synthetic in origin (Table 6). If one considers only small molecules (reducing the total by 77 to 193; Table 7), then the synthetic figure goes up to 31.6%, marginally greater than in our previous report.[3] As reported previously,[1−3] these synthetic drugs tend to be of two basic chemotypes, the azole-based antifungals and the quinolone-based antibacterials.

Six small-molecule drugs were approved in the antibacterial area from January 2006 to December 2010. Three were classified as ND, with the first, retapamulin (**5**), being a semi-synthetic modification of the well-known pleuromutilin structure by GSK in 2007 and the second being ceftobiprole medocaril, a cephalosporin prodrug (**6**) from the Roche spin-off company Basilea in 2008 in Switzerland and Canada. The compound was later withdrawn as of September 2010 by Basilea/Janssen-Cilag (J&J), and it is currently back in phase III trials, with Johnson and Johnson having terminated their license. The third agent was the modified vancomycin telavancin (**7**) by Astellas Pharma in conjunction with Theravance in 2009. The three synthetic antibacterials in this time frame were the fluoroquinolones garenoxacin (**8**) from Astellas Pharma in 2007,

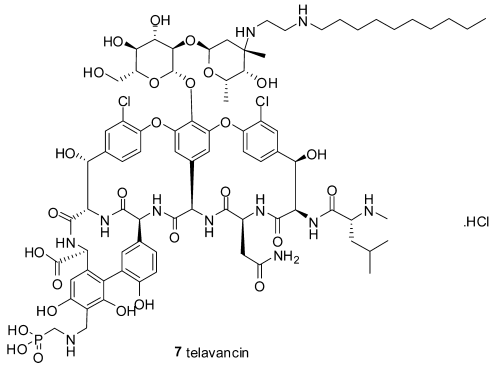
Table 5. Antiparasitic Drugs from 01/01/1981 to 12/01/2010 Organized Alphabetically by Generic Name within Source

generic name	trade name	year introduced	volume	page	source
artemisinin	Artemisin	1987	ARMC 23		N
ivermectin	Mectizan	1987	ARMC 23	336	N
arteether	Artemotil	2000	DNP 14	22	ND
artemether	Artemetheri	1987	I 90712		ND
artesunate	Arinate	1987	I 91299		ND
eflornithine HCl	Ornidyl	1990	DNP 04	104	ND
mefloquine HCI	Fansimef	1985	ARMC 21	329	ND
albendazole	Eskazole	1982	I 129625		S
halofantrine	Halfan	1988	ARMC 24	304	S
lumefantrine	?	1987	I 269095		S
quinfamide	Amenox	1984	ARMC 20	322	S
atovaquone	Mepron	1992	ARMC 28	326	S*
bulaquine/ chloroquine	Aablaquin	2000	DNP 14	22	S*
trichomonas vaccine	Gynatren	1986	I 125543		V



5 retapamulin

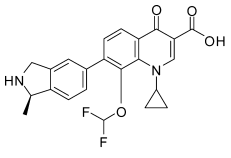
6 ceftobiprole medocaril



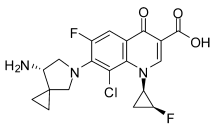
7 telavancin .HCl

Table 7. Small-Molecule Anti-infective (Bacterial, Fungal, Parasitic, and Viral) Drugs (n = 193)

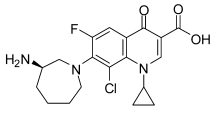
indication	total	N	ND	S	S/NM	S*	S*/NM
antibacterial	104	10	67	26			1
antifungal	28		3	22	3		
antiparasitic	13	2	5	4		2	
antiviral	48		4	9	2	23	10
total	193	12	79	61	5	25	11
percentage	100	6.2	40.9	31.6	2.6	13	5.7



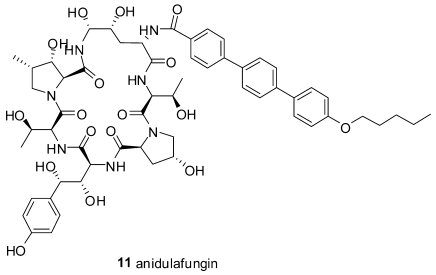
8 garenoxacin



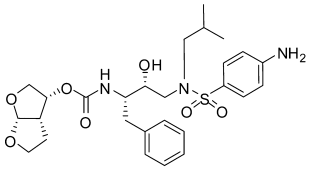
9 sitafloxacin



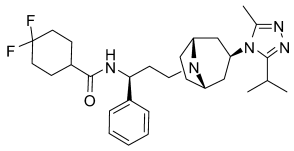
10 besifloxacin



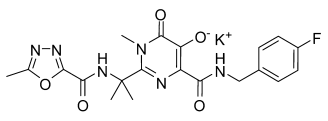
11 anidulafungin



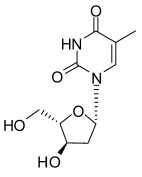
12 darunavir



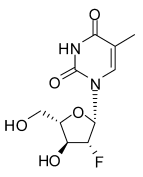
13 maraviroc



14 raltegravir



15 telbivudine



16 clevudine

sitafloxacin from Daiichi (**9**) in 2008, and besifloxacin (**10**) from Bausch and Lomb in 2009. Overall, in the antibacterial area, as shown in Table 7, small molecules account for 104 agents, with "N" and "ND" compounds accounting for just under 75% of the approved agents.

In the antifungal area, only one drug was approved in the 2006 to 2010 time frame. This was the echinocandin derivative anidulafungin (ND; **11**), approved for use in the U.S. in early 2006, and was covered in the 2007 review but without a structure. As is the case with a significant number of compounds, the final company was not the originator. This molecule was first synthesized by Lilly under the code number LY-303366, then

Table 6. All Anti-infective (Bacterial, Fungal, Parasitic, and Viral) Drugs (n = 270)

indication	total	B	N	ND	S	S/NM	S*	S*/NM	V
antibacterial	118		10	67	26			1	14
antifungal	29	1		3	22	3			
antiparasitic	14		2	5	4		2		1
antiviral	109	14		4	9	2	23	10	47
total	270	15	12	79	61	5	25	11	62
percentage	100	5.6	4.4	29.3	22.6	1.8	9.3	4	23

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Table 8. Anticancer Drugs from 01/01/1981 to 12/31/2010 Organized Alphabetically by Generic Name within Source

generic name	trade name	year introduced	volume	page	source
	Rexin-G	2007	I 346431		B
131I-chTNT		2007	I 393351		B
alemtuzumab	Campath	2001	DNP 15	38	B
bevacizumab	Avastin	2004	ARMC 40	450	B
catumaxomab	Removab	2009	DNP 23	18	B
celmoleukin	Celeuk	1992	DNP 06	102	B
cetuximab	Erbitux	2003	ARMC 39	346	B
denileukin diftitox	Ontak	1999	ARMC 35	338	B
H-101		2005	DNP 19	46	B
ibritumomab	Zevalin	2002	ARMC 38	359	B
interferon α-2a	Roferon-A	1986	I 204503		B
interferon, γ-1a	Biogamma	1992	ARMC 28	332	B
interleukin-2	Proleukin	1989	ARMC 25	314	B
mobenakin	Octin	1999	ARMC 35	345	B
nimotuzumab	BIOMAb EFGR	2006	DNP 20	29	B
ofatumumab	Arzerra	2009	DNP 23	18	B
panitumumab	Vectibix	2006	DNP 20	28	B
pegaspargase	Oncaspar	1994	ARMC 30	306	B
rituximab	Rituxan	1997	DNP 11	25	B
sipuleucel-T	Provenge	2010	I 259673		B
tasonermin	Beromun	1999	ARMC 35	349	B
teceleukin	Imumace	1992	DNP 06	102	B
tositumomab	Bexxar	2003	ARMC 39	364	B
trastuzumab	Herceptin	1998	DNP 12	35	B
aclarubicin	Aclacin	1981	P090013		N
angiotensin II	Delivert	1994	ARMC 30	296	N
arglabin	?	1999	ARMC 35	335	N
masoprocol	Actinex	1992	ARMC 28	333	N
paclitaxel	Taxol	1993	ARMC 29	342	N
paclitaxel nanoparticles	Abraxane	2005	DNP 19	45	N
paclitaxel nanoparticles	Nanoxel	2007	I 422122		N
pentostatin	Nipent	1992	ARMC 28	334	N
peplomycin	Pepleo	1981	P090889		N
romidepsin	Istodax	2010	DNP 23	18	N
trabectedin	Yondelis	2007	ARMC 43	492	N
solamargines	Curaderm	1989	DNP 03	25	NB
alitretinoin	Panretin	1999	ARMC 35	333	ND
amrubicin HCl	Calsed	2002	ARMC 38	349	ND
belotecan hydrochloride	Camtobell	2004	ARMC 40	449	ND
cabazitaxel	Jevtana	2010	I 287186		ND
cladribine	Leustatin	1993	ARMC 29	335	ND
cytarabine ocfosfate	Starsaid	1993	ARMC 29	335	ND
docetaxel	Taxotere	1995	ARMC 31	341	ND
elliptinium acetate	Celiptium	1983	P091123		ND
epirubicin HCI	Farmorubicin	1984	ARMC 20	318	ND
eribulin	Halaven	2010	I 287199		ND
etoposide phosphate	Etopophos	1996	DNP 10	13	ND
exemestane	Aromasin	1999	DNP 13	46	ND
formestane	Lentaron	1993	ARMC 29	337	ND
fulvestrant	Faslodex	2002	ARMC 38	357	ND
gemtuzumab ozogamicin	Mylotarg	2000	DNP 14	23	ND
hexyl aminolevulinate	Hexvix	2004	I 300211		ND
idarubicin hydrochloride	Zavedos	1990	ARMC 26	303	ND
irinotecan hydrochloride	Campto	1994	ARMC 30	301	ND
ixabepilone	Ixempra	2007	ARMC 43	473	ND
mifamurtide	Junovan	2010	DNP 23	18	ND
miltefosine	Miltex	1993	ARMC 29	340	ND
pirarubicin	Pinorubicin	1988	ARMC 24	309	ND
pralatrexate	Folotyn	2009	DNP 23	18	ND
talaporfin sodium	Laserphyrin	2004	ARMC 40	469	ND
temsirolimus	Toricel	2007	ARMC 43	490	ND

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Table 8. continued

generic name	trade name	year introduced	volume	page	source
topotecan HCl	Hycamptin	1996	ARMC 32	320	ND
triptorelin	Decapeptyl	1986	I 090485		ND
valrubicin	Valstar	1999	ARMC 35	350	ND
vapreotide acetate	Docrised	2004	I 135014		ND
vinflunine	Javlor	2010	I 219585		ND
vinorelbine	Navelbine	1989	ARMC 25	320	ND
zinostatin stimalamer	Smancs	1994	ARMC 30	313	ND
aminoglutethimide	Cytadren	1981	I 070408		S
amsacrine	Amsakrin	1987	ARMC 23	327	S
arsenic trioxide	Trisenox	2000	DNP 14	23	S
bisantrene hydrochloride	Zantrene	1990	ARMC 26	300	S
carboplatin	Paraplatin	1986	ARMC 22	318	S
flutamide	Drogenil	1983	ARMC 19	318	S
fotemustine	Muphoran	1989	ARMC 25	313	S
heptaplatin/SK-2053R	Sunpla	1999	ARMC 35	348	S
lobaplatin	Lobaplatin	1998	DNP 12	35	S
lonidamine	Doridamina	1987	ARMC 23	337	S
miriplatin hydrate	Miripla	2010	DNP 23	17	S
nedaplatin	Aqupla	1995	ARMC 31	347	S
nilutamide	Anadron	1987	ARMC 23	338	S
oxaliplatin	Eloxatin	1996	ARMC 32	313	S
plerixafor hydrochloride	Mozobil	2009	DNP 22	17	S
porfimer sodium	Photofrin	1993	ARMC 29	343	S
ranimustine	Cymerine	1987	ARMC 23	341	S
sobuzoxane	Parazolin	1994	ARMC 30	310	S
sorafenib	Nexavar	2005	DNP 19	45	S
anastrozole	Arimidex	1995	ARMC 31	338	S/NM
bicalutamide	Casodex	1995	ARMC 31	338	S/NM
bortezomib	Velcade	2003	ARMC 39	345	S/NM
camostat mesylate	Foipan	1985	ARMC 21	325	S/NM
dasatinib	Sprycel	2006	DNP 20	27	S/NM
erlotinib hydrochloride	Tarceva	2004	ARMC 40	454	S/NM
fadrozole HCl	Afema	1995	ARMC 31	342	S/NM
gefitinib	Iressa	2002	ARMC 38	358	S/NM
imatinib mesilate	Gleevec	2001	DNP 15	38	S/NM
lapatinib ditosylate	Tykerb	2007	ARMC 43	475	S/NM
letrazole	Femara	1996	ARMC 32	311	S/NM
nilotinib hydrochloride	Tasigna	2007	ARMC 43	480	S/NM
pazopanib	Votrient	2009	DNP 23	18	S/NM
sunitinib malate	Sutent	2006	DNP 20	27	S/NM
temoporfin	Foscan	2002	I 158118		S/NM
toremifene	Fareston	1989	ARMC 25	319	S/NM
zoledronic acid	Zometa	2000	DNP 14	24	S
azacytidine	Vidaza	2004	ARMC 40	447	S*
capecitabine	Xeloda	1998	ARMC 34	319	S*
carmofur	Mifurol	1981	I 091100		S*
clofarabine	Clolar	2005	DNP 19	44	S*
decitabine	Dacogen	2006	DNP 20	27	S*
doxifluridine	Furtulon	1987	ARMC 23	332	S*
enocitabine	Sunrabin	1983	ARMC 19	318	S*
fludarabine phosphate	Fludara	1991	ARMC 27	327	S*
gemcitabine HCl	Gemzar	1995	ARMC 31	344	S*
mitoxantrone HCI	Novantrone	1984	ARMC 20	321	S*
nelarabine	Arranon	2006	ARMC 42	528	S*
abarelix	Plenaxis	2004	ARMC 40	446	S*/NM
bexarotene	Targretine	2000	DNP 14	23	S*/NM
degarelix	Firmagon	2009	DNP 22	16	S*/NM
pemetrexed disodium	Alimta	2004	ARMC 40	463	S*/NM
raltiterxed	Tomudex	1996	ARMC 32	315	S*/NM
tamibarotene	Amnoid	2005	DNP 19	45	S*/NM
temozolomide	Temodal	1999	ARMC 35	350	S*/NM

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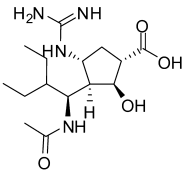
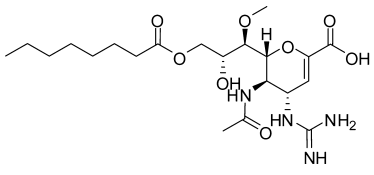
Table 8. continued

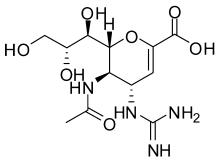
generic name	trade name	year introduced	volume	page	source
vorinostat	Zolinza	2006	DNP 20	27	S*/NM
	Cervarix	2007	I 309201		V
autologous tumor cell-BCG	OncoVAX	2008	DNP 22	17	V
bcg live	TheraCys	1990	DNP 04	104	V
melanoma theraccine	Melacine	2001	DNP 15	38	V
vitespen	Oncophage	2008	DNP 22	17	V



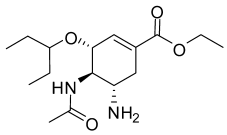
17 peramivir



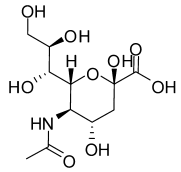
18 laninamavir



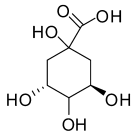
19 zanamivir



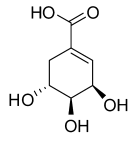
20 oseltamivir



21 *N*-acetylneuraminic acid



22 quinic acid



23 shikimic acid

licensed to Versicor in 1999; Versicor became Vicuron in 2003 and Pfizer purchased Vicuron in 2005.

In contrast to the antibacterial case, in the antifungal area, as shown in Table 7, small molecules account for 28 agents, but in the 30 years of coverage, only three agents fall into the "ND" category, accounting for just over 10% of the approved drugs. This can be seen in the treatment regimens that still use agents such as amphotericin and griseofulvin, which are both listed in the *Integrity* database as being launched in 1958.

In the antiviral area, a very significant number of the agents are vaccines, as mentioned earlier, predominately directed against various serotypes of influenza, as would be expected from the avian flu outbreaks. In the time frame 2006 to 2010, and looking at small molecules, seven drugs were approved for a variety of viral diseases. In contrast to the previous reviews,[1−3] the number of anti-HIV drugs decreased, with only three being reported in the four years since the previous report. These were darunavir (S/NM, **12**) in 2006 from Tibotec/Janssen, an HIV protease inhibitor, the first HIV attachment inhibitor, maraviroc (S, **13**), in 2007, from the joint venture between Pfizer and GSK on anti-HIV therapies, and in the same year the first integrase inhibitor, raltegravir (S, **14**), by Merck. Of definite import during the last five years, however, is the approval of two new drugs for the treatment of hepatitis B in 2006. The first, telbivudine, a simple thymine analogue that is a DNA-polymerase inhibitor with a 2-deoxyribose derivative as the sugar moiety (S*, **15**), was licensed in from Idenix by Novartis. The second, clevudine (S*, **16**), with the same mechanism of action, is also a thymine derivative, but, in this case, the sugar moiety is further substituted by a fluorine atom on the sugar compared to telbivudine. This compound was originally identified at Yale University and the University of Georgia, then was licensed by the Korean company Bukwang, who then sublicensed it to Eisai for further development.

The last two compounds, both of which were approved in 2010, are small-molecule inhibitors of the influenza virus.[99] The first, peramivir (S/NM, **17**), can be considered as a successful in silico derivative, as it was modeled into the sialidase crystal structure by BioCryst (Birmingham, AL, USA), who subsequently licensed it to Green Cross and then Shionogi in Japan for treatment of influenza A and B. The second molecule, laninamivir (ND, **18**), is basically similar in structure to both zanamivir (1999, ND, **19**) and oseltamivir (1999, ND, **20**), both modeled on *N*-acetyl-neuraminic acid (**21**, the substrate of the sialidases) and for which synthetic routes can come from either quinic acid (**22**) or shikimic acid (**23**),[100] with the latter compound being produced from the star anise plant, *Illicium anisatum*,[101] or via fermentation of genetically modified *E. coli* strains.[102,103]

In contrast to the antibacterial and antifungal areas, in the antiviral case, as shown in Table 7, small molecules account for 48 drugs, with only four (or 8%) in the 30 years of coverage falling into the "ND" category. However, consistently we have placed modified nucleosides and peptidomimetics, etc., as falling into the "S*" or "S*/NM" categories. If these are added to the four drugs listed above, then the other than synthetic molecules account for 37, or 57%, overall.

As reported in our earlier analyses,[1−3] there are still significant therapeutic classes where the available drugs are totally synthetic at the present time. These include antihistamines, diuretics, and hypnotics for indications with four or more approved drugs (cf. Table 1), and, as found previously, there are still a substantial number of indications in which there are three or less approved drugs that are also totally synthetic. As mentioned in our earlier reviews,[2,3] due to the introduction of the "NM" subcategory, indications such as antidepressants, bronchodilators, and cardiotonics now have substantial numbers that, although formally "S" or "S*", fall into the "S/NM" or "S*/NM" subcategories, as the information in the literature points to their interactions at active sites as competitive inhibitors.

With anticancer drugs (Table 8), in the time frame covered (01/1981−12/2010) there were 128 NCEs in toto, with the number of nonbiologicals, aka small molecules, being 99 (77%), a slightly lower percentage compared to the last review's value of 81%.[3] Using the total of 99 as being equal to 100%, the breakdown was as follows, with the values from the last review inserted for comparison: N (11, 11.1% {9, 11.1%}), NB (1, 1% {none}), ND (32, 32.3% {25; 30.9%}), S (20, 20.2% {18, 22.2%}), S/NM (16, 16.2% {12, 14.8%}), S* (11, 11.1% {11, 13.6%}),

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Table 9. All Anticancer Drugs (1940s to 12/31/2010) Organized Alphabetically by Generic Name within Source[a]

generic name	year introduced	reference	page	source
131I-chTNT	2007	I 393351		B
alemtuzumab	2001	DNP 15	38	B
aldesleukin	1992	ARMC 25	314	B
bevacizumab	2004	ARMC 40	450	B
catumaxomab	2009	DNP 23	18	B
celmoleukin	1992	DNP 06	102	B
cetuximab	2003	ARMC 39	346	B
denileukin diftitox	1999	ARMC 35	338	B
H-101	2005	DNP 19	46	B
ibritumomab	2002	ARMC 38	359	B
interferon alfa2a	1986	I 204503		B
interferon alfa2b	1986	I 165805		B
interferon, gamma-1a	1992	ARMC 28	332	B
interleukin-2	1989	ARMC 25	314	B
mobenakin	1999	ARMC 35	345	B
nimotuzumab	2006	DNP 20	29	B
ofatumumab	2009	DNP 23	18	B
panitumumab	2006	DNP 20	28	B
pegaspargase	1994	ARMC 30	306	B
Rexin-G (trade name)	2007	I 346431		B
rituximab	1997	DNP 11	25	B
sipuleucel-T	2010	I 259673		B
tasonermin	1999	ARMC 35	349	B
teceleukin	1992	DNP 06	102	B
tositumomab	2003	ARMC 39	364	B
trastuzumab	1998	DNP 12	35	B
aclarubicin	1981	I 090013		N
actinomycin D	1964	FDA		N
angiotensin II	1994	ARMC 30	296	N
arglabin	1999	ARMC 35	335	N
asparaginase	1969	FDA		N
bleomycin	1966	FDA		N
carzinophilin	1954	Japan Antibiotics		N
chromomycin A3	1961	Japan Antibiotics		N
daunomycin	1967	FDA		N
doxorubicin	1966	FDA		N
leucovorin	1950	FDA		N
masoprocol	1992	ARMC 28	333	N
mithramycin	1961	FDA		N
mitomycin C	1956	FDA		N
neocarzinostatin	1976	Japan Antibiotics		N
paclitaxel	1993	ARMC 29	342	N
paclitaxel nanoparticles (Abraxane)	2005	DNP 19	45	N
paclitaxel nanoparticles (Nanoxel)	2007	I 422122		N
pentostatin	1992	ARMC 28	334	N
peplomycin	1981	I 090889		N
romidepsin	2010	DNP 23	18	N
sarkomycin	1954	FDA		N
streptozocin	pre-1977	Carter		N
testosterone	pre-1970	Cole		N
trabectedin	2007	ARMC 43	492	N
vinblastine	1965	FDA		N
vincristine	1963	FDA		N
solamargines	1989	DNP 03	25	NB
alitretinoin	1999	ARMC 35	333	ND
amrubicin HCl	2002	ARMC 38	349	ND
belotecan hydrochloride	2004	ARMC 40	449	ND
cabazitaxel	2010	I 287186		ND
calusterone	1973	FDA		ND
cladribine	1993	ARMC 29	335	ND
cytarabine ocfosfate	1993	ARMC 29	335	ND
dexamethasone	1958	FDA		ND
docetaxel	1995	ARMC 31	341	ND
dromostanolone	1961	FDA		ND
elliptinium acetate	1983	P091123		ND
epirubicin HCl	1984	ARMC 20	318	ND
eribulin	2010	I 287199		ND
estramustine	1980	FDA		ND
ethinyl estradiol	pre-1970	Cole		ND
etoposide	1980	FDA		ND
etoposide phosphate	1996	DNP 10	13	ND
exemestane	1999	DNP 13	46	ND
fluoxymesterone	pre-1970	Cole		ND
formestane	1993	ARMC 29	337	ND
fosfestrol	pre-1977	Carter		ND
fulvestrant	2002	ARMC 38	357	ND
gemtuzumab ozogamicin	2000	DNP 14	23	ND
goserelin acetate	1987	ARMC 23	336	ND
hexyl aminolevulinate	2004	I 300211		ND
histrelin	2004	I 109865		ND
hydroxyprogesterone	pre-1970	Cole		ND
idarubicin hydrochloride	1990	ARMC 26	303	ND
irinotecan hydrochloride	1994	ARMC 30	301	ND
ixabepilone	2007	ARMC 43	473	ND
leuprolide	1984	ARMC 20	319	ND
medroxyprogesterone acetate	1958	FDA		ND
megesterol acetate	1971	FDA		ND
methylprednisolone	1955	FDA		ND
methyltestosterone	1974	FDA		ND
mifamurtide	2010	DNP 23	18	ND
miltefosine	1993	ARMC 29	340	ND
mitobronitol	1979	FDA		ND
nadrolone phenylpropionate	1959	FDA		ND
norethindrone acetate	pre-1977	Carter		ND
pirarubicin	1988	ARMC 24	309	ND
pralatrexate	2009	DNP 23	18	ND
prednisolone	pre-1977	Carter		ND
prednisone	pre-1970	Cole		ND
talaporfin sodium	2004	ARMC 40	469	ND
temsirolimus	2007	ARMC 43	490	ND
teniposide	1967	FDA		ND
testolactone	1969	FDA		ND
topotecan HCl	1996	ARMC 32	320	ND
triamcinolone	1958	FDA		ND
triptorelin	1986	I 090485		ND
valrubicin	1999	ARMC 35	350	ND
vapreotide acetate	2004	I 135014		ND
vindesine	1979	FDA		ND
vinflunine	2010	I 219585		ND
vinorelbine	1989	ARMC 25	320	ND
zinostatin stimalamer	1994	ARMC 30	313	ND
amsacrine	1987	ARMC 23	327	S
arsenic trioxide	2000	DNP 14	23	S
bisantrene hydrochloride	1990	ARMC 26	300	S
busulfan	1954	FDA		S
carboplatin	1986	ARMC 22	318	S

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Table 9. continued

generic name	year introduced	reference	page	source
carmustine (BCNU)	1977	FDA		S
chlorambucil	1956	FDA		S
chlortrianisene	pre-1981	Boyd		S
cis-diamminedichloroplatinum	1979	FDA		S
cyclophosphamide	1957	FDA		S
dacarbazine	1975	FDA		S
diethylstilbestrol	pre-1970	Cole		S
flutamide	1983	ARMC 19	318	S
fotemustine	1989	ARMC 25	313	S
heptaplatin/SK-2053R	1999	ARMC 35	348	S
hexamethylmelamine	1979	FDA		S
hydroxyurea	1968	FDA		S
ifosfamide	1976	FDA		S
lenalidomide	2005	DNP 19	45	S
levamisole	pre-1981	Boyd		S
lobaplatin	1998	DNP 12	35	S
lomustine (CCNU)	1976	FDA		S
lonidamine	1987	ARMC 23	337	S
mechlorethanamine	1958	FDA		S
melphalan	1961	FDA		S
miriplatin hydrate	2010	DNP 23	17	S
mitotane	1970	FDA		S
nedaplatin	1995	ARMC 31	347	S
nilutamide	1987	ARMC 23	338	S
nimustine hydrochloride	pre-1981	Boyd		S
oxaliplatin	1996	ARMC 32	313	S
pamidronate	1987	ARMC 23	326	S
pipobroman	1966	FDA		S
plerixafor hydrochloride	2009	DNP 22	17	S
porfimer sodium	1993	ARMC 29	343	S
procarbazine	1969	FDA		S
ranimustine	1987	ARMC 23	341	S
razoxane	pre-1977	Carter		S
semustine (MCCNU)	pre-1977	Carter		S
sobuzoxane	1994	ARMC 30	310	S
sorafenib	2005	DNP 19	45	S
thiotepa	1959	FDA		S
triethylenemelamine	pre-1981	Boyd		S
zoledronic acid	2000	DNP 14	24	S
anastrozole	1995	ARMC 31	338	S/NM
bicalutamide	1995	ARMC 31	338	S/NM
bortezomib	2003	ARMC 39	345	S/NM
camostat mesylate	1985	ARMC 21	325	S/NM
dasatinib	2006	DNP 20	27	S/NM
erlotinib hydrochloride	2004	ARMC 40	454	S/NM
fadrozole HCl	1995	ARMC 31	342	S/NM
gefitinib	2002	ARMC 38	358	S/NM
imatinib mesilate	2001	DNP 15	38	S/NM
lapatinib ditosylate	2007	ARMC 43	475	S/NM
letrazole	1996	ARMC 32	311	S/NM
nafoxidine	pre-1977	Carter		S/NM
nilotinib hydrochloride	2007	ARMC 43	480	S/NM
pazopanib	2009	DNP 23	18	S/NM
sunitinib malate	2006	DNP 20	27	S/NM
tamoxifen	1973	FDA		S/NM
temoporfin	2002	I 158118		S/NM
toremifene	1989	ARMC 25	319	S/NM
aminoglutethimide	1981	FDA		S*
azacytidine	2004	ARMC 40	447	S*
capecitabine	1998	ARMC 34	319	S*
carmofur	1981	I 091100		S*
clofarabine	2005	DNP 19	44	S*
cytosine arabinoside	1969	FDA		S*
decitabine	2006	DNP 20	27	S*
doxifluridine	1987	ARMC 23	332	S*
enocitabine	1983	ARMC 19	318	S*
floxuridine	1971	FDA		S*
fludarabine phosphate	1991	ARMC 27	327	S*
fluorouracil	1962	FDA		S*
ftorafur	1972	FDA		S*
gemcitabine HCl	1995	ARMC 31	344	S*
mercaptopurine	1953	FDA		S*
methotrexate	1954	FDA		S*
mitoxantrone HCI	1984	ARMC 20	321	S*
nelarabine	2006	ARMC 42	528	S*
thioguanine	1966	FDA		S*
uracil mustard	1966	FDA		S*
abarelix	2004	ARMC 40	446	S*/NM
bexarotene	2000	DNP 14	23	S*/NM
degarelix	2009	DNP 22	16	S*/NM
pemetrexed disodium	2004	ARMC 40	463	S*/NM
raltiterxed	1996	ARMC 32	315	S*/NM
tamibarotene	2005	DNP 19	45	S*/NM
Temozolomide	1999	ARMC 35	350	S*/NM
vorinostat	2006	DNP 20	27	S*/NM
autologous tumor cell-BCG	2008	DNP 22	17	V
bcg live	1990	DNP 04	104	V
Cervarix (trade name)	2007	I 309201		V
melanoma theraccine	2001	DNP 15	38	V
vitespen	2008	DNP 22	17	V

[a]Note that in Figure 9 there are three vertical bars corresponding to the drugs noted in the "year introduced" column above as "pre-1970", "pre-1977", and "pre-1981". The entries under these three categories are not repeating the other two, as the drugs are individually distinct entries, but their actual dates cannot be determined.

and S*/NM (8, 8.1% {6, 7.4%}). Thus, using our criteria, only 20.2% of the total number of small-molecule anticancer drugs were classifiable into the "S" (synthetic) category. Expressed as a proportion of the nonbiologicals/vaccines, then 79 of 99 (79.8%) were either natural products per se or were based thereon, or mimicked natural products in one form or another.

In this current review, we have continued as in our previous contribution (2007)[3] to reassess the influence of natural products and their mimics as leads to anticancer drugs from the beginnings of antitumor chemotherapy in the very late 1930s to early 1940s. By using data from the FDA listings of antitumor drugs, coupled to our previous data sources and with help from Japanese colleagues, we have been able to specify the years in which all but 18 of the 206 drugs listed in Table 9 were approved. We then identified these other 18 agents by inspection of three time-relevant textbooks on antitumor treatment,[73,104,105] and these were added to the overall listings using the lead authors' names as the source citation.

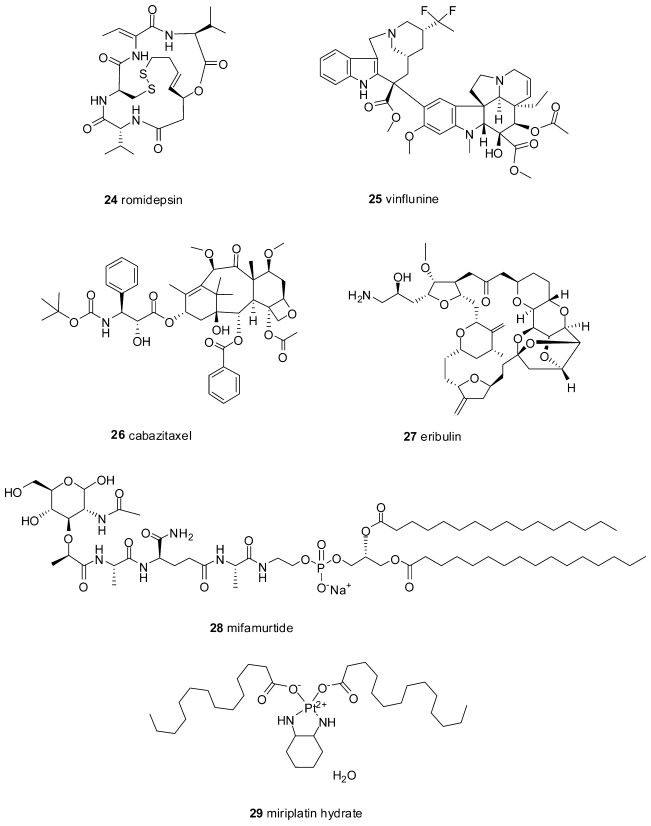
Table 10. Antidiabetic Drugs from 01/01/1981 to 12/31/2010 Organized Alphabetically by Generic Name within Source

generic name	trade name	year introduced	volume	page	source
biphasic porcine insulin	Pork Mixtard 30	1982	I 303034		B
hu neutral insulin	Insuman	1992	I 255451		B
hu insulin zinc suspension	Humulin Zn	1985	I 091584		B
human insulin Zn suspension	Humulin L	1985	I 302828		B
human neutral insulin	Novolin R	1991	I 182551		B
insulin aspart	NovoRapid	1999	DNP 13	41	B
insulin aspart/IA protamine	NovoMix 30	2001	DNP 15	34	B
insulin determir	Levemir	2004	DNP 18	27	B
insulin glargine	Lantus	2000	DNP 14	19	B
insulin glulisine	Apidra	2005	DNP 19	39	B
insulin lispro	Humalog	1996	ARMC 32	310	B
isophane insulin	Humulin N	1982	I 091583		B
mecasermin	Somazon	1994	DNP 08	28	B
oral insulin	Oral-lyn	2005	DNP 19	39	B
porcine isophane insulin	Pork Insulatard	1982	I 302757		B
porcine neutral insulin	Pork Actrapid	1998	I 302749		B
pulmonary insulin	Exubera	2005	DNP 20	23	B
soluble insulin	Velosulin BR	1986	I 091581		B
voglibose	Basen	1994	ARMC 30	313	N
acarbose	Glucobay	1990	DNP 03	23	ND
extenatide	Byetta	2005	DNP 19	40	ND
liraglutide	Victoza	2009	DNP 23	13	ND
miglitol	Diastabol	1998	ARMC 34	325	ND
triproamylin acetate	Normylin	2005	DNP 19	40	ND
glimepiride	Amaryl	1995	ARMC 31	344	S
mitiglinide calcium hydrate	Glufast	2004	ARMC 40	460	S
pioglitazone NCl	Actos	1999	ARMC 35	346	S
repaglinide	Prandin	1998	ARMC 34	329	S
alogliptin benzoate	Nesina	2010	I 405286		S/NM
epalrestat	Kinedak	1992	ARMC 28	330	S/NM
rosiglitazone maleate	Avandia	1999	ARMC 35	348	S/NM
saxagliptin	Onglyza	2009	DNP 23	13	S/NM
sitagliptin	Januvia	2006	DNP 20	23	S/NM
tolrestat	Alredase	1989	ARMC 25	319	S/NM
troglitazone	Rezulin	1997	ARMC 33	344	S/NM
vildagliptin	Galvus	2007	ARMC 43	494	S/NM
nateglinide	Starsis	1999	ARMC 35	344	S*

Inspection of Figure 9 and Table 9 shows that, over the whole category of anticancer drugs approved worldwide, the 206 approved agents can be categorized as follows: B (26; 13%), N (27; 13%), NB (1; 0.5%), ND (57; 28%), S (44; 21%), S/NM (18; 9%), S* (20; 10%), S*/NM (8; 4%), and V (5; 2%). If one then removes the high molecular weight materials (biologicals and vaccines), reducing the overall number to 175 (100%), the number of naturally inspired agents (i.e., N, ND, S/NM, S*, S*/NM) is 131 (74.9%). Etoposide phosphate and various nanoparticle formulations of Taxol have been included for the sake of completeness.

There are at least two points of definitive interest to natural products scientists in these figures over the past few years, in particular in the last four (2006−2010), when the sources of approved antitumor drugs are considered. Thus, the first antitumor agent that is a "botanical" (or NB), polyphenon E, was approved by the FDA in 2007 for treatment of genital warts linked to human papilloma viruses (HPV),[106] although one can argue from a chemical aspect that Curaderm, which is a mixture of solamargines and was approved in 1989, was the first of these. We have now listed it as an "NB" rather than an "N" in Table 8. Polyphenon E is currently in a number of trials against various cancers as both a preventative and as a direct agent against chronic lymphocytic leukemia and bladder and lung cancers at the phase II level and in breast cancer at the phase I level, with a number of trials being sponsored by NCI.

What is perhaps of equal or perhaps higher significance is that if one looks at the seven antitumor agents approved in 2010, roughly 20 years after the move away from natural product-based discovery programs by big pharmaceutical companies, then one, romidepsin (**24**), a histone deacetylase inhibitor (HDAC), is a microbial natural product[107−110] without any modification, and, although it has been synthesized, this compound is still produced by fermentation. Of the remaining six, four are derived from natural products, with three, vinflunine (**25**), cabazitaxel (**26**), and the totally synthetic halichondrin B-derived eribulin (**27**), being tubulin-interactive agents, but all binding to different sites on tubulin. Although the vinca and taxane sites are reasonably well described, eribulin appears to bind to site(s) that are different from these.[111,112] The remaining one in this category, mifamurtide (**28**), is a derivatized muramyl dipeptide approved for the treatment of osteosarcoma.[113] The remaining small



molecule, miriplatin hydrate (**29**), is totally synthetic and is a new member of a very old class, the platinates, although its structure is dissimilar to others in the class in having what might be described as myristyl ester linkages to the platinum atom, giving it significant lipid solubility.[114]

In our earlier papers, the number of nonsynthetic antitumor agents approximated 60% for other than biological/vaccines, without using the "NM" subcategory. The corresponding figure obtained by removing the "NM" subcategory in this analysis is 60%. Thus, the proportion has remained similar in spite of some reassignments of sources and the continued use of combinatorial chemistry as a source of test substances.

In the case of the antidiabetic drugs, for both diabetes I and II, the numbers since our last review have increased by five from 32 to 37 (Table 10), with one of the five falling into the "ND" category (cf. discussion on liragultide below). However, one biologic for which much was expected, being the first inhaled product, Exubera, was approved in 2005 by the FDA and then withdrawn in 2008. We have, however, still included it in the tabulation. Four of the other five fall into the "S/NM" category, but the remaining one, liraglutide,[115] is a very interesting derivative of the glucagon-like peptide-1 (GLP-1) and can best be described as [*Nε*-[(*Nα*-hexadecanoyl)-γ-L-Glu]-L-Lys26,L-Arg34]-GLP-1(7−37), where two amino acids have been changed in the 7 to 37 portion of the sequence, followed by addition of lipid "tails". Further information on the utility of GLP-1 agonists can be found in the very recent review by Marre and Penformis.[116]

DISCUSSION

As alluded to in our last two reviews,[2,3] the decline or leveling of the output of the R&D programs of the pharmaceutical companies has continued, with the number of drugs of all types dropping in 2006 to 40 NCEs launched, of which 19 (48%) were classified in the "other than small molecules" or "B/V" categories. The corresponding figures for the next four years (2007−2010) are as follows. In 2007 there were 44 NCEs launched with 18 (41%) classified as "B/V". In 2008, 38 NCEs were launched with 14 (37%) classified as "B/V". In 2009, 42 NCEs were launched with 18 (43%) classified as "B/V". Then in the last year of this analysis, 2010, there were 33 NCEs launched with 13 (39%) classified as "B/V". Thus, one can see that an average of 42% of all NCEs in this five-year time frame were biologicals or vaccines, and as mentioned earlier, the numbers of vaccines during this time period may have been underestimated.

As mentioned in the discussion of the antitumor agents and the dramatic influence of natural product structures in the approvals in 2010, we would be remiss if comment was not made on one other very important compound also approved that year. The compound in question is fingolimod (**30**, Gilenya), the first orally active compound for once-a-day treatment of patients with relapsing forms of multiple sclerosis. The details of the derivation of this compound from an old fungal metabolite known as myriocin (**31**) and the many years of modifications required to produce the drug have been told in detail in two recent reviews.[117,118] What is also of significance is the recent report that fingolimod (**30**) also might have activity as a radiosensitizing agent in the treatment of prostate cancer.[119]

Although combinatorial chemistry continues to play a major role in the drug development process, as mentioned earlier, it is noteworthy that the trend toward the synthesis of complex natural product-like libraries has continued. Even including these newer methodologies, we still cannot find another de novo combinatorial compound approved anywhere in the world, although reliable data are not on hand on approvals in Russia and the People's Republic of China at this time. We think that it is appropriate to re-echo the comments by Danishefsky that were used in the 2007 review:

> *In summary, we have presented several happy experiences in the course of our program directed toward bringing to bear nature's treasures of small molecule natural products on the momentous challenge of human neurodegenerative diseases. While biological results are now being accumulated for systematic disclosure, it is already clear that there is considerable potential in compounds obtained through plowing in the landscape of natural products. Particularly impressive are those compounds that are obtained through diverted total synthesis, i.e., through methodology, which was redirected from the original (and realized) goal of total synthesis, to encompass otherwise unavailable congeners. We are confident that the program will lead, minimally, to compounds that are deserving of serious preclinical follow-up. At the broader level, we note that this program will confirm once again (if further confirmation is, indeed, necessary) the extraordinary advantages of small molecule natural products as sources of agents, which interject themselves in a helpful way in various physiological processes.We close with the hope and expectation that enterprising and hearty organic chemists will not pass up the unique head start that natural products provide in the quest for new agents and new directions in medicinal discovery. We would chance to predict that even as the currently fashionable "telephone directory" mode of research is subjected to much overdue scrutiny and performance-based assessment, organic chemists in concert with biologists and even clinicians will be enjoying as well as exploiting*$_{120}$*the rich troves provided by nature's small molecules.*

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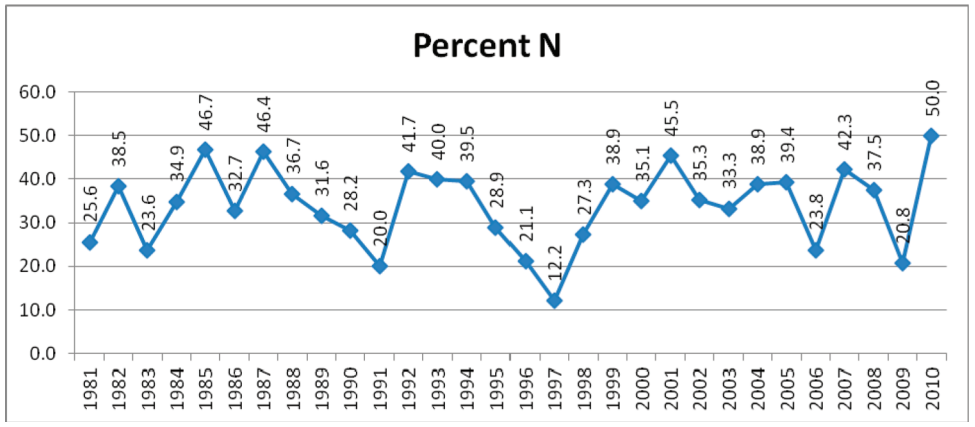

Figure 5. Percent N/NB/ND by year, 1981–2010.

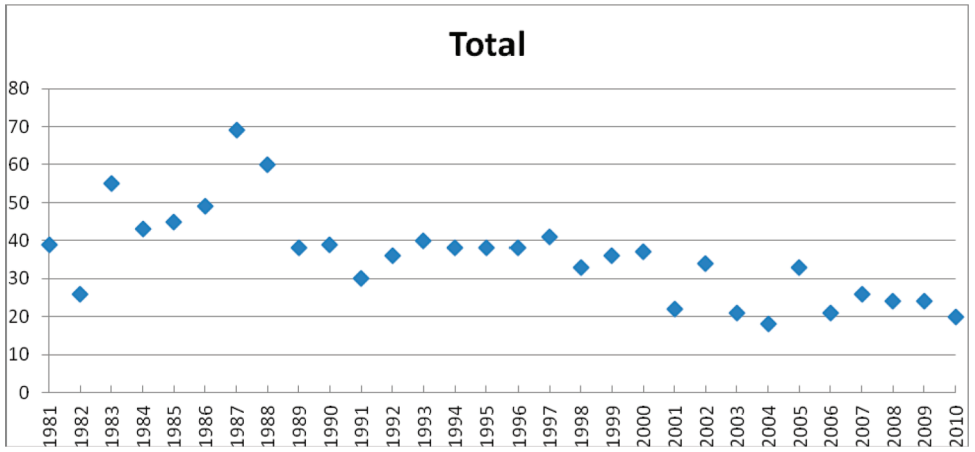

Figure 6. Total small molecules by year, 1981–2010.

A rapid analysis of the entities approved from 2006 to 2010 indicated that there were significant numbers of antitumor, antibacterial, and antifungal agents approved as mentioned above, with the unexpected showing, as exemplified in Figures 5 and 6, that in 2010 of the 20 small molecules approved, the second lowest number in the 30 years of analysis covered in this review, fully half were natural products or directly derived therefrom, with the majority of these being in the antitumor area, 10 years after the approval of the first protein tyrosine kinase inhibitor, Gleevec, in 2001. Included in the 2010 antitumor approvals was eribulin (**27**), to our knowledge the most complex drug yet approved made totally by synthesis.

It is highly probable that in the near future totally synthetic variations on complex natural products will be part of the arsenal of physicians. One has only to look at the extremely elegant syntheses of complex natural products reported recently by Baran and his co-workers to visualize the potential of coupling very active and interesting natural products with the skills of synthetic chemists in academia and industry.[121−124] Also of great significance is the modeling of reactions based on Nature such as those described recently by Furst and Stephenson.[125] Further examples of where selective modification via synthesis of very active peptidic-based molecules can also be seen from the recent paper by Luesch's group on improvements of the in vivo antitumor activity of the apratoxins, molecules produced by cyanobacteria.[126]

It is often not appreciated that the major hurdle in bringing a totally synthetic complex molecule to market is not the basic synthesis but the immense problems faced by process chemists in translating research laboratory discoveries to commercial items.[127,128] In the case of eribulin, the process chemistry group utilized selective crystallization steps rather than chromatography in order to provide the intermediates and the final product itself.

In this review, as we stated in 2003 and 2007,[2,3] we have *yet again* demonstrated that natural products play a dominant role in the discovery of leads for the development of drugs for the treatment of human diseases. As we mentioned in earlier articles, some of our colleagues argued (though not in press, only in personal conversations at various forums) that the introduction of categories such as "S/NM" and "S*/NM" is an overstatement of the role played by natural products in the drug discovery process. On the contrary, we would still argue that these further serve to illustrate the inspiration provided by Nature to receptive organic chemists in devising ingenious syntheses of structural mimics to compete with Mother Nature's longstanding substrates. Even if we discount these categories, the continuing and overwhelming contribution of natural products to the expansion of the chemotherapeutic armamentarium is clearly evident, as demonstrated in Figures 5 and 6, and as we stated in our earlier papers, much of Nature's "treasure trove of small molecules" remains to be explored, particularly from the marine and microbial environments.

From the perspective of microbes and their role(s) as sources of novel bioactive entities, it is now becoming quite evident that there are molecules for which the production depends upon the

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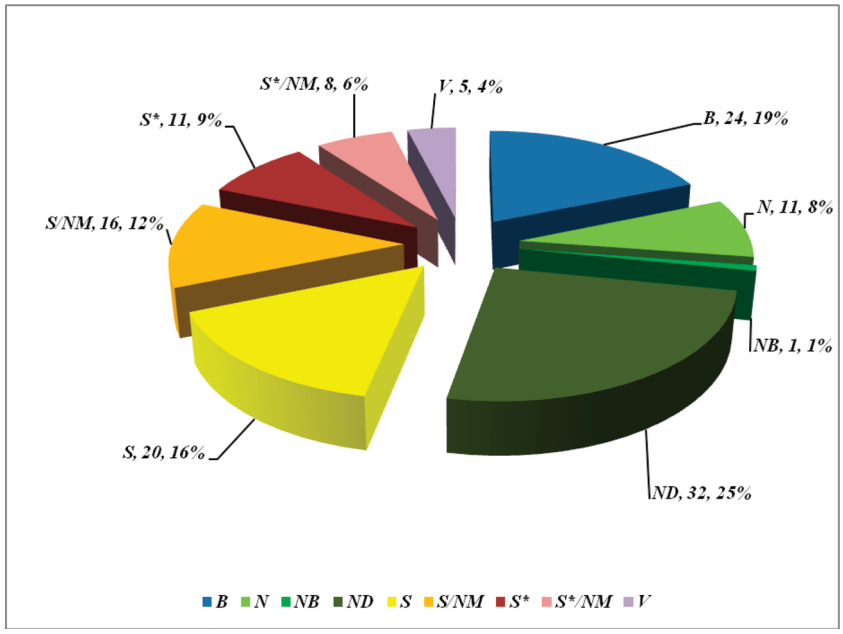


Figure 7. All anticancer drugs, 1981–2010.

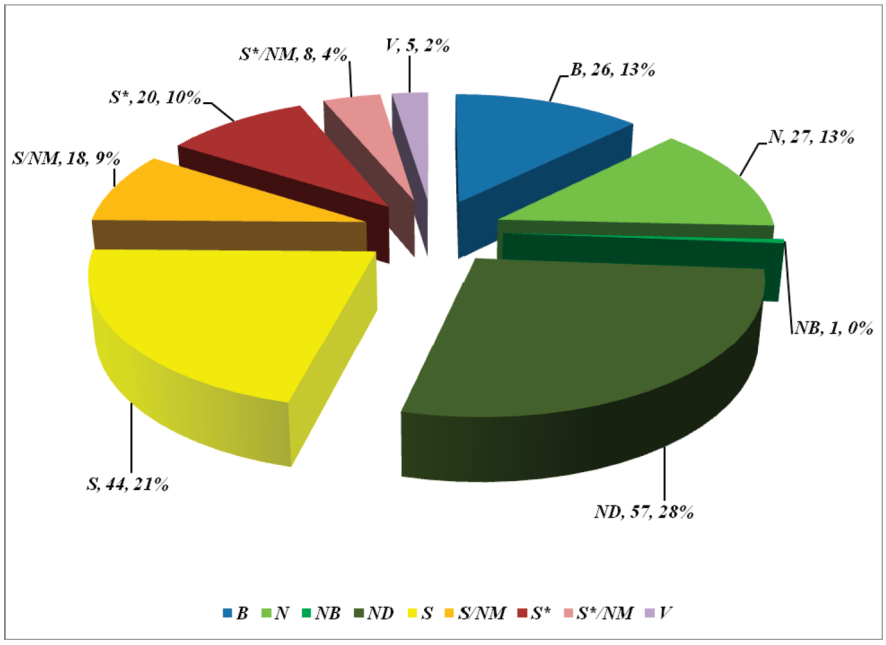
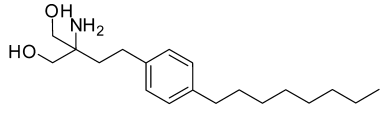


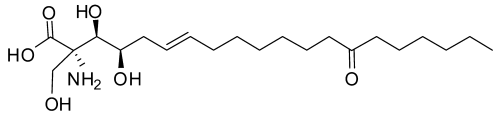
Figure 8. All anticancer drugs 1940s–2010 by source.

interaction among organisms from similar and also, at times, widely different taxa.[129] Recent examples include activation of silent gene clusters in fungi,[130] or the activations of natural product biosyntheses in *Streptomyces* by mycolic acid-containing bacteria,[131] and the production of marine natural products via interactions between sponges and their associated microbes.[132]

Over the past few years, some data have been published indicating, but not as yet fully proving, that a number of fungi isolated from a significant number of different terrestrial plants may contain the full biosynthetic cluster for Taxol production.[133] The one piece missing in the biosynthetic process, the presence of the gene for taxadiene synthetase, was identified, but the production of the metabolite was not fully confirmed in



30 fingolimod



31 myriocin

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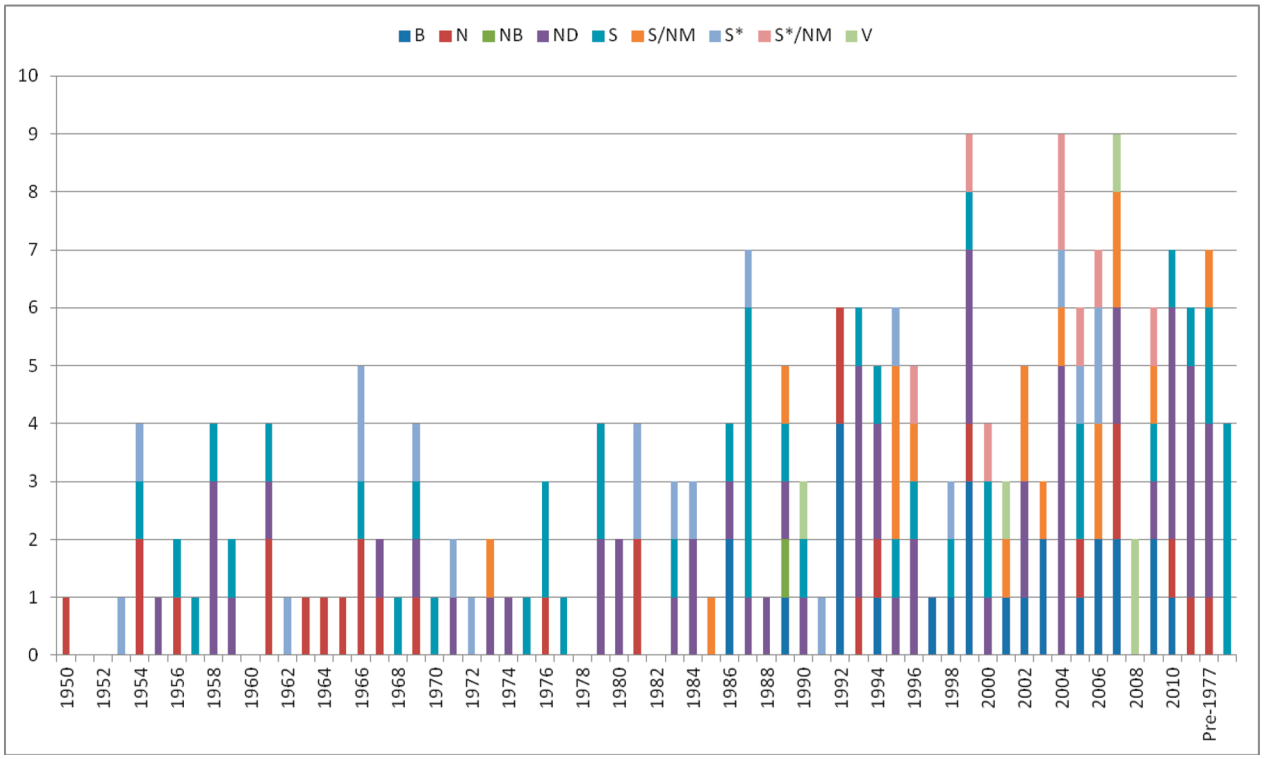

Figure 9. All anticancer drugs 1940s–2010 by year/source. Due to space limitations, only the legend for the center "pre-1977" column shows in this plot on the RHS of "2010". The LH column legend is "pre-1970"and the RH column legend is "pre-1980".

the view of some.[134,135] The possibilities relating to the production of this agent via fungi have been discussed recently by Flores-Bustamente et al.,[136] and recently further evidence of production from a *Taxus globosa* source was reported.[137]

A point emphasized in the review by Flores-Bustamente et al.[136] is effectively the same as those made following the reports a few years ago of multiple unexpected (silent) gene clusters in *Aspergillus nidulans* by Bok et al.[138] That work demonstrated that one has to be able to find the "genetic on-switch" to be able to obtain expression of such clusters outside of the host, as exemplified by further work from the Wisconsin group.[139] Similarly, as recently demonstrated by the group from the Leibnitz Institute in Jena following full genomic analyses of interactions between *Aspergillus nidulans* and *Streptomyces rapamycinicus*, the majority of biosynthetic clusters are "silent" under normal laboratory growth conditions. The interaction between these two microbes switched on a previously unrecognized PKS cluster that encoded the production of orsellinic acid, its derivative lecanoric acid, and the cathepsin K inhibitors F-9775A and F-9775B.[140] In addition to these papers, the reader's attention is also drawn to the excellent review article by Gunatilaka[141] on this subject, which, since its publication in 2006, has been cited over 100 times to date with reports showing materials isolated from plant endophytes. As a result, investigators need to consider all possible routes to novel agents.

To us, a multidisciplinary approach to drug discovery, involving the generation of truly novel molecular diversity from natural product sources, combined with total and combinatorial synthetic methodologies, and including the manipulation of biosynthetic pathways, will continue to provide the best solution to the current productivity crisis facing the scientific community engaged in drug discovery and development.

Once more, as we stated in our 2003 and 2007 reviews,[2,3] we strongly advocate *expanding*, not decreasing, the exploration of Nature as a source of novel active agents that may serve as the leads and scaffolds for elaboration into desperately needed efficacious drugs for a multitude of disease indications. A very recent commentary by Carter in the review journal *Natural Products Reports* shows that such a realization might be closer than one may think.[142]

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

An Excel 2003 workbook with the full data sets is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.
The opinions discussed in this review are those of the authors and are not necessarily those of the U.S. Government.

■ DEDICATION

Dedicated to Dr. Gordon M. Cragg, formerly Chief, Natural Products Branch, National Cancer Institute, Frederick, Maryland, for his pioneering work on the development of natural product anticancer agents and, on a more personal note, for his advice, support, and friendship to me (D.J.N.) over the last twenty-plus years. May his advice and help continue for a long time into the future.

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