

**SUPERINTENDENCIA DE INDUSTRIA Y COMERCIO
DIRECCIÓN DE NUEVAS CREACIONES**

2020
Bogotá, D.C.,

Abogada
MARGARITA CASTELLANOS ABONDANO
info@castellanosyco.co

ASUNTO	Radicación	10 049 261
	Trámite	11
	Evento	378
	Actuación	519
	Oficio	17 896
	Folios	20

Patente de Invención



Patente de Modelo de Utilidad

Via Nacional

Via PCT (Fase Nacional)



Capítulo I



Capítulo II

No. Solicitud Internacional

PCT/US2008/079441

Fecha de Presentación Internacional

10/Octubre/2008

Como resultado del Examen de Fondo realizado, con fundamento en el Artículo 45 de la Decisión 486 de la Comisión de la Comunidad Andina, se comunica:

1. Documentos estudiados

Descripción:	Folios 48 a 74	27/Abril/2010
Reivindicaciones:	Folios 75 a 77	27/Abril/2010
Dibujos:	Folios 79 a 87	27/Abril/2010
Prioridad:	US 60 979 643	12/Octubre/2007

2. Análisis de la Prioridad

Se acepta la reivindicación de prioridad porque esta solicitud fue presentada dentro del plazo establecido (Art. 9 D 486) y su contenido técnico corresponde con el de la prioridad reivindicada.

3. Objeto de la invención

Título de la solicitud: "Forma cristalina 1 de 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida".

El problema planteado en esta solicitud consiste en la necesidad de suministrar formas cristalinas de 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida (ABT-888) que se puedan elaborar de manera reproducible".

Para resolver este problema técnico la solicitud en estudio proporciona la forma cristalina 1 de 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida, la cual, cuando se mide a -100°C en el sistema cristalino tetragonal y grupo espacial P43212 con radiación a 0.7107 Å, se caracteriza por los parámetros de valores reticulares a,

b y c de $8.218 \text{ \AA} \pm 0.002 \text{ \AA}$, $8.218 \text{ \AA} \pm 0.002 \text{ \AA}$ y $36.06 \text{ \AA} \pm 0.002 \text{ \AA}$, respectivamente y valores α , β y γ de 90° .

El objeto de la presente Solicitud se relaciona con la Clasificación Internacional de Patentes (CIP): C07D487/04, A61K31/4184, A61P35/00.

4. Excepción a la Patentabilidad (Art 20 D 486 literal (d))

El objeto de la reivindicación 4 no es patentable de acuerdo con el Art citado.

5. De la Solicitud de Patente

Reivindicaciones (Art 30 D 486, Art 22 PCT)

La reivindicación 1 presenta un error en la traducción, porque contiene la palabra "and". Se solicita realizar la corrección correspondiente.

Las reivindicaciones 1 - 3 y 5 no son claras cuando emplean el término "aproximadamente" porque es impreciso, por lo cual no permite distinguir la invención del estado de la técnica.

La reivindicación 2 no es clara porque se refieren a una forma cristalina pero esta no se caracteriza apropiadamente debido a que no presenta el patrón de difracción de rayos X en mono cristal, el patrón de difracción de rayos X en polvo (DRXP) con por lo menos los 20 picos correspondientes a las intensidades de los haces difractados o a los espacios interplanares d_{hkl} según los índices de Miller (hkl) medidos de acuerdo con el ángulo de difracción de Bragg 2θ en el intervalo más representativo comprendido entre 5° hasta 90° , las espectroscopías Raman e IR, la espectroscopía RMN- C^{13} , o, los métodos de análisis térmico: TGA, DTA y DSC. Se solicita caracterizar la forma cristalina de acuerdo a lo que se encuentre debidamente soportado en la descripción.

Las reivindicaciones 3 y 5 no son claras porque aunque hacen referencia a la composición farmacéutica y al proceso de obtención de la forma cristalina de la reivindicación 1 respectivamente, no se encuentra declarada la dependencia a esta reivindicación; además, se encuentran definidas por características técnicas esenciales de una forma cristalina sin que corresponda a lo encabezado en cada una de ellas. Se sugiere declarar la dependencia de las reivindicaciones 3 y 5 a la reivindicación 1, eliminando de ellas la descripción de la forma cristalina.

La reivindicación 5 no es clara cuando define el proceso de obtención de la forma cristalina de 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida por la disolución del compuesto en un solvente, sin definir el solvente, lo cual es impreciso, no permite distinguir la invención del estado de la técnica, así como tampoco indica la manera, el método o las condiciones esenciales en que se deba realizar esta etapa del proceso. Se solicita definir claramente los solventes empleados en esta etapa, así como las condiciones en que debe realizarse, de acuerdo a lo que esté soportado en la descripción.

La reivindicación 5 no es clara cuando emplea la expresión "hacer que la forma cristalina 1 de 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida exista en la mezcla, dicha forma cristalina 1 de 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida, cuando se aísla y se mide a aproximadamente -100°C en el sistema

cristalino tetragonal y grupo espacial P43212 con radiación a 0.7107 Å, se caracteriza por los parámetros de valores reticulares a, b y c de 8.218 Å ± 0.002Å, 8.218 Å ± 0.002Å y 36.06 Å ± 0.002Å , respectivamente y valores α, β y γ de 90°", porque es un resultado a alcanzar, no definen al proceso porque la invención no queda definida por el resultado a alcanzar, puesto que la reivindicación incluiría no sólo la solución propuesta por el solicitante, sino todas las alternativas presentes o futuras que lleguen a ese resultado. Además, no describe el proceso por sus características esenciales como una etapa o alguna condición específica en la que debiera realizarse. Se sugiere reemplazarlo por las características esenciales, estructurales o funcionales, que contribuyen a la obtención de ese efecto, de acuerdo a lo soportado en la descripción.

La reivindicación 6 no es clara cuando emplea el término "aislamiento de la forma cristalina" porque es impreciso, no permite distinguir la invención del estado de la técnica, no indica la manera, el método o las condiciones esenciales en que se deba realizar esta etapa del proceso. Se solicita definir claramente el método de aislamiento de la forma cristalina de acuerdo a lo que esté soportado en la descripción.

La reivindicación 7 no es clara porque aunque hace referencia al proceso de obtención de la forma cristalina de la reivindicación 1, no se encuentra declarada la dependencia a esta reivindicación. Además, emplea los términos "cristalizar" y "recristalizar" sin definir, las condiciones como los solventes, sus proporciones, entre otras, que permitan a la persona del oficio versada en la materia reproducir la invención. Se solicita declarar la dependencia de la reivindicación 7 a la 1, así como definir claramente las condiciones en las que se debe llevar a cabo la cristalización o la re-cristalización para llegar al objeto de la invención, de acuerdo a lo que esté debidamente soportado en la descripción.

6. Determinación del Estado de la Técnica

El estado de la técnica se determinó con base en la fecha de presentación de la solicitud de prioridad 12 de octubre de 2007 y se encontraron los siguientes documentos que anticipan el objeto de esta solicitud:

Ítem	Documento	Título	Fecha de Publicación
D1	US2006/229289	1H-benzimidazole-4-carboxamides substituted with a quaternary carbon at the 2-position are potent PARP inhibitors	12/Octubre/2006
D2	Artículo ¹	Crystalline solids	2001

D1
http://worldwide.espacenet.com/publicationDetails/biblio?CC=US&NR=2006229289&KC=&FT=E&locale=eng_EP, divulga (reivindicaciones 11 y 17), el compuesto 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida, y composiciones farmacéuticas que lo contienen.

D2 (Folios 116 - 121) enseña el estudio del polimorfismo como una tarea rutinaria dentro del campo farmacéutico en la preformulación de preparados farmacéuticos y que la variedad de formas cristalinas de un compuesto permiten variar propiedades

¹ Vippagunta S, et al; Crystalline solids; Advanced Drug Delivery Reviews; (48); 2001; 3 - 26; folios 116-121.

como la solubilidad, estabilidad, velocidad de disolución entre otras, así como su caracterización mediante los parámetros de red a, b y c y los respectivos valores de α , β y γ .

7. Examen de Patentabilidad (Art 14 D486)

Nivel Inventivo (Art18 D486)

La reivindicación 1 consiste en la forma cristalina 1 de 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida, la cual, cuando se mide a -100°C en el sistema cristalino tetragonal y grupo espacial P4₃2₁2 con radiación a 0.7107 Å, se caracteriza por los parámetros de valores reticulares a, b y c de 8.218 Å ± 0.002Å, 8.218 Å ± 0.002Å y 36.06 Å ± 0.002Å , respectivamente y valores α , β y γ de 90°.

Comparación de las características técnicas esenciales, con las del estado de la técnica:

Características esenciales	D1	D2
Forma cristalina 1 de 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida	Compuesto 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida (reivindicaciones 14 y 17)	Enseña que el fenómeno de polimorfismo (formas cristalinas) es la capacidad de cualquier elemento o compuesto para cristalizar en más de un sistema cristalino y es un trabajo habitual en el campo de preformulación farmacéutico.
Cuando se mide a -100°C en el sistema cristalino tetragonal y grupo espacial P4 ₃ 2 ₁ 2 con radiación a 0.7107 Å, se caracteriza por los parámetros de valores reticulares a, b y c de 8.218 Å ± 0.002Å, 8.218 Å ± 0.002Å y 36.06 Å ± 0.002Å , respectivamente y valores α , β y γ de 90°	No se menciona	Enseña la caracterización de formas cristalinas mediante los parámetros de red a, b y c y los respectivos valores de α , β y γ .

Aproximación método problema-solución para polimorfos (formas cristalinas)

1. Determinación del estado de la técnica más cercano:

El documento D1 se considera el estado de la técnica cercano a la invención definida en la reivindicación 1 porque divulgan el compuesto 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida (reivindicaciones 11 y 17).

2. Determinación de las diferencias técnicas de la invención con respecto al estado del estado de la técnica más cercano:

La diferencia entre la invención definida en la reivindicación 1 y el compuesto del documento D1, consiste en que revelan de manera específica una forma cristalina caracterizada por los parámetros de red del sistema cristalino monoclinico.

3. Determinación del efecto técnico obtenido por las diferencias técnicas de la invención con respecto al estado de la técnica más cercano:

Según la descripción de la solicitud efecto técnico que logra la diferencia es proporcionar una forma cristalina 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida con distintas propiedades físicas y mecánicas.

4. Establecimiento del problema técnico objetivo a solucionar con base en el estado de la técnica más cercano:

El problema técnico objetivo que pretende resolver esta invención se puede formular

como la necesidad de obtener formas cristalinas del compuesto 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida con distintas propiedades físicas y mecánicas.

5. Comprobación de la solución al problema técnico objetivo de la solicitud:

En ninguna parte de la descripción se encuentra soporte de las propiedades físicas y mecánicas superiores de la forma cristalina respecto del compuesto del estado del arte. Por lo anterior, no se puede comprobar la solución al problema técnico objetivo planteado en la solicitud porque no se realiza una comparación técnica de las propiedades del compuesto de la invención y del estado de la técnica más cercano que pueda ser reproducido por la persona del oficio versada en la materia.

Por lo tanto se puede concluir que no existe un efecto técnico probado, porque no se demuestra las ventajas relacionadas con las propiedades físicas y mecánicas reclamadas en la actual solicitud, con respecto a la forma sólida del compuesto divulgado en D1.

Por lo tanto se puede concluir que no existe un efecto técnico probado, porque no se demuestra las ventajas relacionadas con las propiedades físicas y mecánicas estabilidad de la forma cristalina del compuesto 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida reclamada en la actual solicitud, con respecto a la forma sólida del mismo compuesto divulgada en D1.

6. Evaluar si habría sido obvio solucionar el problema técnico objetivo por la invención reivindicada:

De tal manera que la solución al problema técnico planteado por la invención reclamada se considera obvia porque la anterioridad D2, ya divulga que las diferentes formas cristalinas para un mismo compuesto difieren en sus propiedades fisicoquímicas tales como la solubilidad, estabilidad, velocidad de disolución, higroscopicidad, biodisponibilidad entre otras, y es además una práctica habitual en estudios de preformulación dentro de los cuales se incluyen rigurosos trabajos para determinar su presencia en los medicamentos con el fin de evitar su inestabilidad o falta de efectividad (fl 116, pg. 4). Una vez establecido que el compuesto (en este caso aplicable al compuesto 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida) presenta polimorfismo, existen procedimientos con los cuales el preformulador puede preparar las diversas formas en cantidades más grandes para su evaluación adicional y adecuarlas para incorporar en las formas.

También es conocido en el campo técnico que los polimorfos son diferentes arreglos estructurales dentro de un cristal de una misma molécula o sustancia, por lo tanto una persona del oficio normalmente versada en la materia, conociendo que en D1 ya se divulga una forma sólida de 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida, y que en D2 se conoce que el fenómeno de polimorfismo se da ampliamente en los medicamentos de uso farmacéutico, esta persona se encontraría motivada a utilizar métodos como los revelados en D2 para identificar las formas polimórficas de la molécula en cuestión, que además pueden ser analizadas por métodos de cristalografía conocidos (fls 116 y 118, pgs. 5-6 y 13 - 14). De tal manera, no es posible concluir que la identificación de la forma cristalina 1 reclamada en la actual solicitud envuelva actividad inventiva, como quiera que la molécula misma ya era conocida con anterioridad; es decir, la identificación de la forma cristalina reclamada ya sea mediante los parámetros de red a , b y c y los respectivos valores de α , β y γ o caracterizada por la técnica de DRX, no representa un avance técnico real y tampoco un salto cualitativo a la regla técnica porque el efecto asociado no fue

demostrado en la descripción de la solicitud, comoquiera que no se encontró alguna prueba o ensayo que permitiera determinar las ventajas reales de la forma cristalina 1 de 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida con respecto a la forma sólida del mismo compuesto conocida con anterioridad que permita probar, un efecto realmente inesperado asociado con las propiedades físicas y mecánicas.

En consecuencia, una persona del oficio normalmente versada en la materia, encontraría la sugerencia o motivación suficiente aplicando los métodos y conocimientos que se tiene sobre el polimorfismo revelados en D2, a la forma sólida de 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida divulgada en D1, con el fin de determinar la existencia de la forma cristalina 1 del mismo compuesto, tal como la reivindicada.

De acuerdo con lo expuesto, la reivindicación 1 y sus dependientes 2 - 3 no cumplen con el requisito de nivel inventivo (Art. 18).

La reivindicación 5 consiste en un proceso para hacer la forma cristalina 1 de 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida, que comprende: proveer una mezcla que comprende 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida y solvente, en donde la 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida se disuelve completamente en el solvente.

Comparación de las características técnicas esenciales, con las del Estado de la Técnica:

Características esenciales	D1	D2
Proceso para hacer la forma cristalina 1 de 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida), que comprende:	2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida (reivindicaciones 14 y 17)	No se menciona
Proveer una mezcla que comprende 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida) y solvente, en donde la 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida) se disuelve completamente en el solvente	No se menciona	Los polimorfos se crean como consecuencia de un proceso de agregación en una solución (fl 116, pg. 5)

El documento D1 se considera el estado de la técnica cercano a la invención definida en la reivindicación 2 porque divulga el compuesto 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida.

La diferencia entre la invención, definida en la reivindicación 5 y lo divulgado en D1 consiste en que enseña el proceso para hacer la forma cristalina 1 de dicho compuesto.

El efecto que logra el incluir esta característica es que proporciona un proceso para la obtención de la forma cristalina 1 de 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida.

Por lo tanto, el problema técnico objetivo que pretende resolver esta invención se puede formular como la necesidad de suministrar un proceso para la elaboración de una forma cristalina de 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida.

Sin embargo, es de conocimiento común para la persona del oficio versada en la materia que la formación de formas cristalinas se da por un proceso de agregación molecular del compuesto en una solución del mismo, tal como también lo enseña D2 (fl 116, pg. 5, col. derecha).

En consecuencia, la persona del oficio normalmente versada en la materia, se vería suficientemente motivada a disolver el compuesto 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida, en un solvente, según lo divulgado en D2, para llegar así al objeto de la reivindicación 5 de la solicitud., por lo cual se considera obvia.

Conclusión: la reivindicación 5 cumple el requisito de novedad (Art. 16), pero no cumple con el requisito de nivel inventivo (Art. 18).

Además, D2 enseña que la forma cristalina se puede aislar por cristalización (fl 116, pg. 5). Puesto que la reivindicación dependiente 6 no menciona características inventivas adicionales tampoco se puede considerar inventiva.

La reivindicación 7 consiste en un proceso para hacer a forma cristalina 1 de 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida, que comprende hacer reacción de una sal ácida o diácida de 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida y una base y cristalizar o recrystalizar la 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida en la forma cristalina 1 de 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida, cristallar o recrystalizar la forma cristalina 1 de 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida a partir de un forma sólida, semisólida, cera o aceite de 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida que se mezcla con uno o más de un solvente de la reacción de desprotonación.

Comparación de las características técnicas esenciales, con las del Estado de la Técnica:		
Características esenciales	D1	D2
Proceso para hacer la forma cristalina 1 de 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida), que comprende:	2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida (reivindicaciones 14 y 17)	No se menciona
hacer reacción de una sal ácida o diácida de 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida y una base	No se menciona	No se menciona
cristallar o recrystalizar a partir de un forma sólida, semisólida, cera o aceite de 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida en la forma cristalina 1 de 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida que se mezcla con uno o más de un solvente de la reacción de desprotonación	No se menciona	Los polimorfos se crean como consecuencia de un proceso de agregación en una solución (fl 116, pg. 5)

El documento D1 se considera el estado de la técnica cercano a la invención definida en la reivindicación 2 porque divulga el compuesto 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida.

La diferencia entre la invención, definida en la reivindicación 5 y lo divulgado en D1 consiste en que enseña el proceso para hacer la forma cristalina 1 de dicho compuesto en el medio de reacción de obtención del mismo compuesto por la adición de uno o más solventes en donde cristaliza la forma cristalina 1, objeto de la invención.

El efecto que logra el incluir esta característica es que proporciona un proceso para la obtención de la forma cristalina 1 de 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida.

Por lo tanto, el problema técnico objetivo que pretende resolver esta invención se puede formular como la necesidad de suministrar un proceso para la elaboración de

una forma cristalina de 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida.

Sin embargo, es de conocimiento común para la persona del oficio versada en la materia que la formación de formas cristalinas se da por un proceso de agregación molecular del compuesto en una solución del mismo, tal como también lo enseña D2 (fl 116, pg. 5, col. derecha). Es decir, aunque la obtención de la forma sólida del compuesto sea por la reacción de su sal con una base, e fundamento de la obtención de la forma cristalina sigue siendo el proceso de agregación molecular en una solución del compuesto, por lo cual puede ser necesaria la adición de uno o más solventes adicionales al medio de reacción, lo cual dará las condiciones para la obtención del polimorfo.

En consecuencia, la persona del oficio normalmente versada en la materia, se vería suficientemente motivada a agregar un solvente al medio de obtención del compuesto 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida, en un solvente, para disolver el compuesto 2-((R)-2-metil-pirrolidin-2-il)-1H-benzimidazol-4-carboxamida y cristalizar una forma cristalina, según lo divulgado en D2, para llegar así al objeto de la reivindicación 7 de la solicitud, por lo cual se considera obvia.

Conclusión: la reivindicación 7 cumple el requisito de novedad (Art. 16), pero no cumple con el requisito de nivel inventivo (Art. 18).

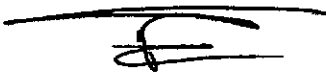
8. Conclusión

Los requisitos de Patentabilidad de la presente Solicitud están afectados así:

Ítem	Documento	Reivindicaciones afectadas	Requisito que afecta
D1	US2006/229289	1 -3 y 5 - 7	Nivel inventivo
D2	Artículo	1 -3 y 5 - 7	Nivel inventivo

En cumplimiento del artículo 45 de la Decisión 486 de la Comisión de la Comunidad Andina, se le indica que debe dar respuesta dentro del término de sesenta (60) días contados a partir de la fecha de notificación de la presente comunicación. En caso de no dar respuesta al presente requerimiento, o si a pesar de la respuesta subsistieran los impedimentos para la concesión, se denegará la patente.

Notifíquese el presente oficio conforme a lo dispuesto en el numeral 5.2, literal e), del capítulo quinto del título primero de la Circular Única No. 10 de 2001.


JOSÉ LUIS SALAZAR LÓPEZ
Director de Nuevas Creaciones (C)

El anterior requerimiento fue notificado por fijación en lista, de fecha 09 OCT. 2012

Elaborado por: Rubiela Pacanchique Vargas *oat*
Revisado por: Jacqueline Alfonso Rozo



ELSEVIER

Advanced
DRUG DELIVERY
Reviews

www.elsevier.com/locate/drugdelrev

Advanced Drug Delivery Reviews 58 (2011) 3–26

Crystalline solids

Sudha R. Vippagunta^a, Harry G. Brittain^b, David J.W. Grant^{a,*}

^a Department of Pharmaceutics, College of Pharmacy, University of Minnesota, Bremer–Olinford Hall, 308 Harvard Street SE, Minneapolis, MN 55455, USA

^b Center for Pharmaceutical Physics, 10 Charles Road, 08404, NJ 08404, USA

Received 18 October 2010; accepted 21 December 2010

Abstract

Many drugs exist in the crystalline solid state due to reasons of stability and ease of handling during the various stages of drug development. Crystalline solids can exist in the form of polymorphs, solvates or hydrates. Phase transitions such as polymorph interconversion, desolvation of solvate, formation of hydrate and conversion of crystalline to amorphous form may occur during various pharmaceutical processes, which may alter the dissolution rate and transport characteristics of the drug. Hence it is desirable to choose the most suitable and stable form of the drug in the initial stages of drug development. The current focus of research in the solid-state area is to understand the origins of polymorphism at the molecular level, and to predict and prepare the most stable polymorph of a drug. The recent advances in computational tools along the prediction of polymorphs of the drug from its molecular structure. Sensitive analytical methods are being developed to understand the nature of polymorphs and to characterize the various crystalline forms of a drug in its dosage form. The aim of this review is to complement the recent advances made in the area of prediction and characterization of polymorphs and solvates, to address the current challenges faced by pharmaceutical scientists and to anticipate future developments. © 2011 Elsevier Science B.V. All rights reserved.

Keywords: Crystallinity; Polymorphs; Hydrates; Solvates; Formulation; Drug substance; Phase transformation; Characterization

Contents

1. Introduction	4
2. Recent advances in the identification, prediction and characterization of polymorphs	6
2.1. Types of polymorphs	6
2.2. Packing polymorphs	7
2.3. Conformational polymorphs	8
2.4. Phase transformations in the solid state	9
2.5. Prediction of polymorphs	11
2.6. Directing the crystallization of specific polymorphs	12
2.7. Characterization of polymorphs using a combination of analytical techniques	13
3. Recent advances in the identification and characterization of hydrates and solvates	14
3.1. Introduction to hydrates and solvates	14
3.2. Structural aspects	15

*Corresponding author. Tel.: +1-612-4341-956; fax: +1-612-4350-699.

E-mail address: grant001@tc.umn.edu (D.J.W. Grant).

0169-029X/\$ – see front matter © 2011 Elsevier Science B.V. All rights reserved.
PII: S0169-029X(11)00091-7

S.R. Vippagunta et al. / Advanced Drug Delivery Reviews 58 (2011) 3–26

3.3. Phase transformation of hydrates and solvates	17
3.4. Prediction of the formation of hydrates and solvates	18
3.5. Characterization of hydrates and solvates	19
4. Current challenges and future directions	19
4.1. Origins of the challenges	19
4.2. Phase transformations during processing	19
4.3. Degree of crystallinity	21
4.4. Characterization of mixtures of polymorphs	23
5. Conclusions	25
References	24

1. Introduction

Most organic and inorganic compounds of pharmaceutical relevance can exist in one or more crystalline forms. When applied to solids, the adjective *crystalline* implies an ideal crystal in which the structural units, termed *unit cells*, are repeated regularly and indefinitely in three dimensions in space. The unit cell has a definite orientation and shape defined by the translational vectors a , b , and c , and hence has a definite volume, V , that contains the atoms and molecules necessary for generating the crystal. Each crystal can be classified as a member of one of seven possible crystal systems or crystal classes that are defined by the relationships between the individual dimensions, a , b , and c , of the unit cell and between the individual angles, α , β , and γ of the unit cell [1,2]. The structure of a given crystal may be assigned to one of the seven crystal systems, to one of the 14 Bravais lattices, and to one of the 230 space groups [1]. All the 230 possible space groups, their symmetries, and the symmetries of their diffraction patterns are compiled in the International Tables for Crystallography [3].

The common crystalline forms found for a given drug substance are polymorphs and solvates. Crystalline polymorphs have the same chemical composition but different internal crystal structures and, therefore, possess different physico-chemical properties. The different crystal structures in polymorphs arise when the drug substance crystallizes in different crystal packing arrangements and/or different conformations. The occurrence of polymorphism is quite common among organic molecules and a large number of polymorphic drug compounds have been noted and catalogued [4–7].

Solvates, also known as pseudopolymorphs, are

crystalline solid adducts containing solvent molecules within the crystal structure, in either stoichiometric or nonstoichiometric proportions, giving rise to unique differences in the physical and pharmaceutical properties of the drug. If the incorporated solvent is water, a solvate is termed a hydrate. Adducts frequently crystallize more easily because two molecules often can pack together with less difficulty than single molecules. While no definite explanations can be given, possible reasons include defect symmetry, adduct-induced conformation changes, and the ability to form hydrogen bonds through the solvent molecules [2,8,9]. Desolvated solvates are produced when a solvate is desolvated and the crystal retains the structure of the solvate [10]. Desolvated solvates are less ordered than their crystalline counterparts and are difficult to characterize, because analytical studies indicate that they are unsolvated materials (or anhydrous crystal forms) when, in fact, they have the structure of the solvated crystal form from which they were derived [11].

Because different crystalline polymorphs and solvates differ in crystal packing, and/or molecular conformation as well as in lattice energy and entropy, there are usually significant differences in their physical properties, such as density, hardness, solubility, refractive index, melting point, enthalpy of fusion, vapor pressure, solubility, dissolution rate, other thermodynamic and kinetic properties and even color [12]. Differences in physical properties of various solid forms have an important effect on the processing of drug substances into drug products [13], while differences in solubility may have important effects on the absorption of the active drug from its dosage form [14], by affecting the dissolution rate and possibly the mass transport of the molecules. These concerns have led to an increased regulatory

interest in understanding the solid-state properties and behavior of drug substances. For approval of a new drug, the drug substance guideline of the US Food and Drug Administration (FDA) states that "appropriate" analytical procedures need to be used to detect polymorphs, hydrates and amorphous forms of the drug substance and also stresses the importance of controlling the crystal form of the drug substance during the various stages of product development [11]. It is very important to control the crystal form of the drug during the various stages of drug development, because any phase change due to polymorph interconversions, desolvation of solvates, formation of hydrates and change in the degree of crystallinity can alter the bioavailability of the drug. When going through a phase transition, a solid drug may undergo a change in its thermodynamic properties, with consequent changes in its dissolution and transport characteristics [15].

Various pharmaceutical processes during drug development significantly influence the final crystalline form of the drug in the dosage form. The various effects of pharmaceutical processing on drug polymorphs, solvates and phase transitions have been described in detail by Brittain and Fieser [16] and will be discussed in later chapters. Briefly, processes such as lyophilization and spray drying may lead to the formation of the amorphous form of drug, which tends to be less stable and more hygroscopic than the crystalline product. Also, processing stresses, such as drying, grinding, milling, wet granulation, oven drying and compaction, are reported to accelerate the phase transitions in pharmaceutical solids. The degree of polymorphic conversion will depend on the relative stability of the phases in question, and on the type and degree of mechanical processing applied. Keeping these factors in mind, it is desirable and usual to choose the most stable polymorphic form of the drug in the beginning and to control the crystal form and the distributions in size and shape of the drug crystals during the entire process of development. The presence of a metastable form during processing or in the final dosage form often leads to instability of drug release as a result of phase transformation [17].

Crystallization plays a critical role in controlling the crystalline form and the distribution in size and shape of the drug. The significance of crystallization

mechanisms and kinetics in directing crystallization pathways of pharmaceutical solids and the factors affecting the formation of crystals have been reviewed in detail by various researchers [12,18,19]. A crystalline phase is created as a consequence of molecular aggregation processes in solution that lead to the formation of nuclei, which achieve a certain size during the nucleation phase to enable growth into macroscopic crystals to take place during the growth phase. The factors affecting the rate and mechanisms by which crystals are formed are: solubility, supersaturation, rate at which supersaturation and desupersaturation occur, diffusivity, temperature, and the reactivity of surfaces towards nucleation. The various forces responsible for holding the organic crystalline solids together, such as nonbonded interactions and hydrogen bonding, have been discussed in detail by Byrn et al. [2] and Eyer [20].

Various analytical methods are being currently used to characterize the crystalline form of the drug during the various steps of processing and development. These methods have been reviewed recently in detail by many authors [7,10,21–25]. The single most valuable piece of information about the crystalline solid, including the existence of polymorphs and solvates, is the molecular and crystalline structure, which is determined by single-crystal X-ray diffraction [2]. Powder X-ray diffraction provides a "fingerprint" of the solid phase and may sometimes be used to determine crystal structure. Once the existence of polymorphism (or solvate formation) is definitely established by single-crystal and powder X-ray diffraction, spectral methods, such as Fourier transform infrared absorption (FTIR) spectroscopy, Fourier transform Raman scattering (FT Raman) spectroscopy, solid-state nuclear magnetic resonance (SSNMR) spectroscopy, ultraviolet and visible (UV–Vis) and/or fluorescence spectroscopy [23] may be employed for further characterization. Of special significance are thermal methods, such as differential scanning calorimetry (DSC), thermogravimetric analysis (TGA) and optical microscopy using a hot stage [24]. These methods are almost always employed for further characterization. Modulated (temperature) differential scanning calorimetry (MDSC) in combination with DSC and optical microscopy are able to identify the glass

transition of amorphous forms with much greater clarity and allow unique insights into the glass transition and polymorphic behavior of drug substances [26].

Because solid-state NMR spectroscopy can be used to study crystalline solids, as well as pharmaceutical dosage forms, this powerful method is finding increasing application in deducing the nature of polymorphic variations [27], such as variations in hydrogen bonding network and molecular conformations among polymorphs [28,29] and for the determination of molecular conformations and mobility of drugs in mixtures and dosage forms [2]. Solid-state ^{13}C -NMR in conjunction with the techniques, known as high power proton decoupling, cross polarization (CP), and magic-angle spinning (MAS) offers information not obtained readily by other techniques. Recently, two-dimensional ^{13}C -solid-state NMR spectroscopy has been used to study the three conformational polymorphs of 5-methyl-2-(2-*nitrophenyl*)amino-3-thiophenecarboxonitrile [30]. Use of two-dimensional NMR and total suppression of spinning side bands (TOSS) pulse sequences allowed the separation of isotropic and anisotropic chemical shifts for the three forms. This is a very powerful method for analyzing differences in the chemical environment and is finding increased application in the study of conformational polymorphism.

With advances in analytical methods, the current focus of research in the solid-state area is to understand polymorphism and pseudopolymorphism at the molecular level. Knowledge of the crystal packing arrangements and the various intermolecular forces involved in the different packing arrangements will help in the prediction and preparation of the most stable polymorphs of a given compound well in advance, to avoid surprises during product development. A current emphasis is on the development of software to predict crystal structures of polymorphs from molecular structures. A thorough understanding of the physicochemical properties of polymorphs and solvates (hydrates) is of primary importance to the selection of a suitable crystalline form and development of a successful pharmaceutical product. Byrn et al. [31] have shown that, by thorough characterization of four different crystalline forms of L-738,167, a fluorogren receptor antagonist by various analytical

techniques, it was possible to determine the suitability of one or two forms for the development of pharmaceutical oral dosage forms.

The present review aims to emphasize the recent advances made in the area of prediction and characterization of polymorphs and solvates, attempts to address the current challenges and problems faced by pharmaceutical scientists and intends to anticipate future development. This review does not attempt to provide solutions to the problems but attempts to review comprehensively the advances made in recent years to help address these problems.

2. Recent advances in the identification, prediction and characterization of polymorphs

2.1. Types of polymorphism

Based on differences in the thermodynamic properties, polymorphs are classified as either enantiomers or monomers, depending upon whether one form can transform reversibly to another or not. In an enantiomeric system, a reversible transition between polymorphs is possible at a definite transition temperature below the melting point. In a monomeric system, no reversible transition is observed between the polymorphs below the melting point. Four useful rules have been developed by Burger and Ramberger [32,33] to determine qualitatively the enantiomeric or monomeric nature of the relationship between polymorphs. These rules are the heat of transition rule, heat of fusion rule, infrared rule and density rule.

If, by use of the above rules, it is established that the polymorphs of a particular drug are enantiomeric or monomeric, then the next goal is to define the thermodynamically stable (or metastable) domain of each crystalline phase of a substance as a function of temperature. The plot of the Gibbs free energy difference, ΔG , against the absolute temperature, T , gives the most complete and quantitative information on the stability relationship of polymorphs [22], with the most stable polymorph having the lowest Gibbs free energy. The ΔG between the polymorphs may be obtained using several techniques operating at

different temperatures, such as solubility [34] and intrinsic dissolution rate. Yu [35] has derived thermodynamic equations to calculate ΔG between two polymorphs and its temperature slope from the melting data. This method is essentially an extension of the heat of fusion rule, which is based on statistical mechanics. Extrapolating ΔG to zero gives an estimate of the transition temperature, from which the existence of monotropy or eutectonropy is inferred. The integration of different types of data provides the ΔG vs. T curve over a wide temperature range and allows the consistency between techniques to be checked [22]. Another approach to establish the order of stability among various polymorphs has been studied using pressure versus temperature plots, e.g., for sulfonamide and piroxicam [36]. This approach is based upon Ostwald's principle of least vapor pressure, according to which the stable polymorph exhibits the lowest vapor pressure. The accuracy of this approach to establish the stability hierarchy among the polymorphs has been shown to be very much dependent on the accuracy of the experimental data.

In recent years, the main focus of research has been the characterization of polymorphs arising from structural differences in the crystal lattice. It has been established for some time that organic molecules are capable of forming different crystal lattices through two different mechanisms. One of the mechanisms is termed *packing polymorphism*, and represents instances where conformationally relatively rigid molecules can be assembled into different three-dimensional structures through the invocation of different intermolecular mechanisms. The other mechanism is termed *conformational polymorphism* and arises when a nonconformationally rigid molecule can be folded into different arrangements, which subsequently can be packed into alternative crystal structures. The distinction between *packing polymorphism* and *conformational polymorphism* is somewhat artificial because different packing arrangements impose different conformations on the molecules, however slight, and different conformations will inevitably pack differently. The structural aspects associated with polymorphs have been reviewed recently [2], as have the analogous features of solvate and hydrate systems [9]. In the next

section, the results of some more recent investigations are discussed.

2.2. Packing polymorphism

An investigation into the structures and charge densities of two polymorphs of *p*-nitrophenol has been performed with the aim of deducing the different modes of inter-molecular hydrogen bonding that lead to the formation of the two structures shown in Fig. 1a and b [37]. A detailed analysis of the charge density of the two forms indicates charge migration from the benzene ring region to the nitro end hydroxyl groups that accompanies the transformation of one form into the other. In addition, polarization of the oxygen lone-pair electrons was found to be substantially larger in the crystal forms than in the free molecule, resulting in considerably larger dipole moments in the solid state.

During the study of a new crystal form (form I) of

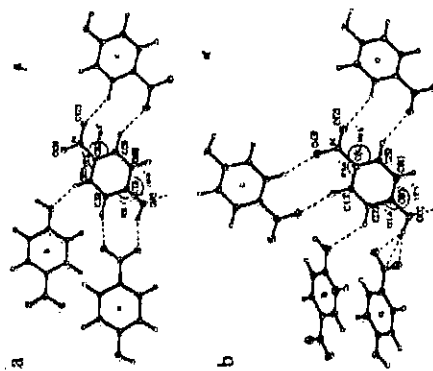


Fig. 1. Molecular packing diagrams of the (a) β polymorph of *p*-nitrophenol, (b) α polymorph of *p*-nitrophenol, showing 30% probability displacement ellipsoids (10%), reproduced with the permission of the American Chemical Society.

chloridazepoxide, it was found that the heat of transition between the two forms (forms I and II) is rather modest, and kinetic factors permit the existence of the metastable phase [38]. Both structures contain four crystallographically independent molecules linked in dimers through hydrogen bonding, but the dimers are packed differently to yield the two crystal forms. Because the dimers in the fundamental units are spaced differently in the two forms, it was proposed that the solid-state enantiomorphic transformation entailed rearrangement of the dimer units.

A different approach has been taken during an evaluation of the different structures formed by sulfathiazole [39]. Using a graph set approach to classify the known structural differences and similarities among the various forms, it became possible to identify packing motifs common to three of the four crystal structures. Fig. 2 shows the unit cells of the polymorphs I, II, III and IV, where molecules are packed as hydrogen-bonded dimers. At the end of the process, the authors were able to deduce possible links between the observed patterns of hydrogen bonding, processes of nucleation, and the crystal growth observed from a number of solvent systems. Interestingly, the analysis did not indicate a relationship between the appearance of a particular polymorph from solution and the growth of its fastest

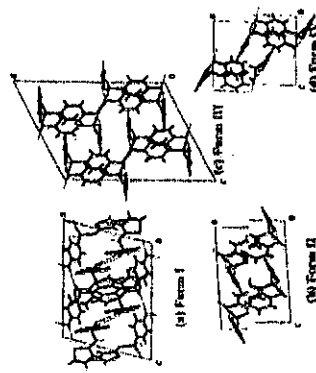


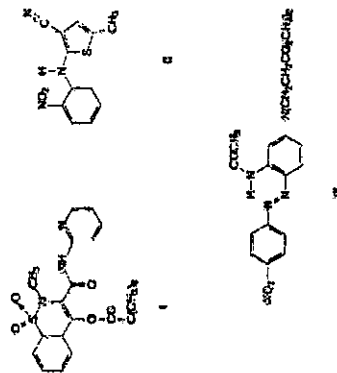
Fig. 2. Unit cells of four polymorphs (I, II, III and IV) of sulfathiazole showing hydrogen bonds, with the donor structure clearly discernible (19%), reproduced with the permission of the Royal Society of Chemistry.

growing surface. Rather, it appeared as if the different solvents affected the process of polymorph formation through their effects on nucleation of the various forms.

2.3. Conformational polymorphism

The conformational polymorphism of the two forms of piroxicam pivalate has been studied in detail [40]. This compound is distinctive in that the high-melting form (polymorph I) contains an anticipated array of associated molecules bound as centrosymmetric dimers through hydrogen bonding, with the azido nitrogen atom acting as the donor and the pyridine nitrogen as the acceptor (Scheme 1, structure I). The low-melting form (polymorph II) consists of molecules of two distinct conformational states coexisting in the same crystal (Fig. 3), but linked through different hydrogen bonding arrangements. This latter feature represents another unusual aspect of the crystallography of the substance.

The existence of different solvent molecules in a crystal lattice can lead to the existence of different packing patterns, and has also been found to influence the molecular conformation of piroxicam hydrochloride in two solvate forms [41]. One form



Scheme 1. Molecular structure of piroxicam pivalate: (I) high-melting form (polymorph I), (II) low-melting form (polymorph II), reproduced with the permission of the Royal Society of Chemistry.

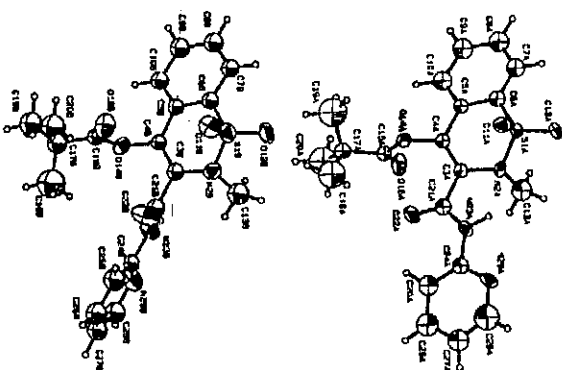


Fig. 3. Conformation of the two independent molecules of protonated paracetamol (1) in polyspace 2. Thermal ellipsoids are drawn at the 40% probability level, and H atoms are shown as spheres of arbitrary radii (40%), reproduced with the permission of the American Pharmaceutical Association.

was obtained as a hemihydrate, and the other as the solvate of isopropanol (2-propanol). In the unit cell of the hemihydrate, one finds two protonated paracetamol and two chloride ions together with one water molecule. Interestingly, the two paracetamol molecules are conformationally nonequivalent, and exhibit a number of different bond angles and torsion angles. In the other form, the unit cell contains one protonated paracetamol molecule, one chloride ion, and one isopropanol molecule disordered along a molecular channel. Furthermore, the conformation of the paracetamol molecule in the isopropanol solvate is different from either molecular conformation observed in the

hemihydrate phase. Crystals of the isopropanol solvate decomposes in the open air at room temperature, because the isopropanol molecules are released easily through the channel. The hemihydrate is relatively stable.

In an impressive fundamental study, the polymorphism of 5-methyl-2-[2-(*o*-tolylphenyl)amino]-3-thiophenecarboxonitrile (Scheme 1, structure 1) has been catalogued [42,43] and discussed in detail [2]. This compound was crystallized as six solvent-free polymorphs, each of which differed in the mode of packing and in molecular conformation. The different conformers yielded sufficient perturbations on the respective molecular orbital so that a variety of crystal colors (red, orange, and yellow) were observed. To obtain a more detailed evaluation of the relative stability, the authors considered a partitioning of polymorphic energy differences into lattice and conformational contributions, and were able to deduce general trends that appeared valid in the absence of hydrogen bonding. The act of crystallization was found to feature an interplay of opposing forces, with perpendicular molecular conformations being favored in fluid solutions, while a preference for planar/high dipole conformers existed in most crystal forms, as shown in Fig. 4 [42]. The unusual polymorphism displayed by this system may result from one or more of the following factors: the preference for perpendicular conformations in solutions, the preference for planar/high dipole conformers in crystals, the formation of inter- and intramolecular hydrogen bonds, and the thermodynamic tendency towards low energy and high entropy.

2.4. Phase transformations in the solid state

Studies of phase transformations in the solid state are important, because the sudden appearance or disappearance of a crystalline form can threaten process development, and can lead to serious pharmaceutical consequences if the transformation occurs in the dosage forms. Hence, an understanding of the kinetics and mechanism of phase transformations is of practical importance. The rearrangement of molecules into a new structure during phase transformation may or may not involve a solvent or vapor phase. To explain the mechanism of solid-solid

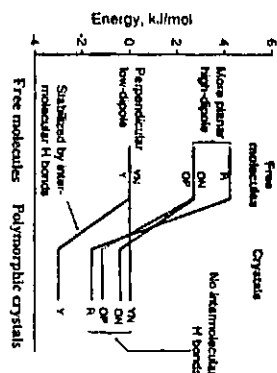


Fig. 4. Comparison of conformational energies and crystal energies of the various polymorphs of 5-methyl-2-[2-(*o*-tolylphenyl)amino]-3-thiophenecarboxonitrile (1). Form K (red prism, m.p. 106.2°C), form Y (yellow prism, m.p. 109.8°C), form OP (orange plates, m.p. 112.7°C), form ON (orange needles, m.p. 114.8°C), form YN (yellow needles, m.p. not measurable) [42], reproduced with the permission of the American Chemical Society.

physical transition, four steps have been proposed: (a) molecular loosening in the initial phase; (b) formation of an intermediate solid solution; (c) nucleation of the new solid phase and (d) growth of the new phase [2]. In an interesting study, Skowronski [44] has proposed a two-environment model to describe the decomposition reaction kinetics of a crystalline solid, aspirin. The decomposition reaction of aspirin is a simple unimolecular thermally-induced autolysis and the reaction proceeds under anhydrous conditions, i.e., water is not a reactant [45]. This model links the chemistry of the solid-state reaction with the molecular mobility of the reactant as the reaction proceeds. The advantage of this model is that it can be used to determine the shelf life of a product from kinetic data gathered at elevated temperatures. Apart from solid-solid physical transformations, solution-mediated physical transformations among polymorphs are also known to occur in processes, such as wet granulation and during dissolution testing.

While the majority of studies have probed the equilibrium properties of polymorphic and solid-state solvated systems, relatively few have been concerned with the dynamics of phase transformation. Byrn et

al. [2] have reviewed briefly the aspect of polymorphic interconversions and the factors affecting the transformations. In one study, the contribution of hydrogen bonding to the $\alpha \rightarrow \beta$ phase change of resorcinol has been detailed [46]. The α form is more stable than the β form at room temperature, but is less dense than the β form. The transition of $\alpha \rightarrow \beta$ at an estimated transition temperature of 337 $\pm$ 1 K is accompanied by an increase in crystal density, with the structure shifting from an open array of molecules (linked through hydrogen bonding) to a denser structure resembling molecular crystals. Through the use of a simple potential model, it was concluded that, during the phase transformation, the energy of the hydrogen bonds decreases along with the extent of such bonding. The energy liberated by this process is almost offset by the enhanced Van der Waals energies associated with the increase in crystal density, and consequently the transition enthalpy is rather small. Accompanying the shifts in hydrogen bonding is a number of effective proton transfers, altering the covalent and ionic portions of the crystal. It was also learned that the increase in entropy produced from the redistribution of protons was of the same order of magnitude as the entropy of the phase transition.

A number of spectroscopic techniques have been used to study the processes associated with a polymorphic transition of 2-(2,4-dinitrophenyl)-5-methylpyridine [47]. The two interconverting structures coexisted over a temperature range of at least 8–9°C. The phase change was associated with a molecular isomerization that translated through the collective changes of a large number of molecules, yielding domains having definite short-range order. The slowly evolving spectroscopy that took place above the transition temperature was interpreted as the annealing of domains into a long-range ordered system. The process of phase transformation appeared to consist of an initial fast redistribution of the mole ratio of the coexisting phases, followed by a much slower process involving a macroscopic relaxation of the system. Although local thermodynamic equilibrium was thought to exist in individual domains, the sigmoidal curve for the temperature range of the phase transition was proposed to arise from nonequilibrium conditions existing among the various types of domains.

A combination of solid-state ^{13}C -NMR spectroscopy and X-ray crystallography was used to study polymorphic transitions in an azobenzene dyestuff, 2'-acetyl-4'-[N,N-bis(2-methyl-1-propyl)amino]-4-nitroazobenzene (Scheme 1, structure III) [48]. This work established that the structure of one polymorph was disordered, and that the process of phase transformation entailed a crank-shaft-type motion of the azo linkage. The ORTEP plots of the two molecular conformations for the X-ray structure determination of structure III at 293 K are shown in Fig. 5. Selective polarization investigation and band shape-fitting experiments were used to deduce the thermodynamic parameters of the exchange process.

Raman spectroscopy was used to study the effect of pressure on the phase transitions in hexamethylbenzene and hexamethyl-4,4'-benzene [49]. The form II $\rightarrow$ form III transition of the partially deuterated substance was found to take place at a lower pressure relative to that of the analogous hexamethylbenzene compound, which was attributed to differences in the energies of the intramolecular methyl torsional vibration in the two crystal forms. In another study performed by the same group, the effects of both temperature and pressure on the phase transitions of tetrafluoro-1,4-benzoquinone were considered [50]. In this system, the changes in en-

vironmental conditions were found to influence a number of intramolecular and intermolecular vibrational modes, yielding conformational changes that in turn produced the observed phase transitions.

2.5. Prediction of polymorph

The main challenge in managing the phenomenon of multiple solid forms of a drug is the inability to predict the number of forms that can be expected in a given case. This prediction would involve quantification of the myriad intermolecular forces within any proposed crystal structure as well as the ability to postulate the likely packing modes for a given molecule in all its configurations [10]. Accurate theoretical prediction of polymorphs from studies of molecular dynamics and crystal structure generation would be of outstanding importance in drug research [36].

More research is now being directed towards developing computational tools to understand the nature of polymorphism and to predict polymorphic forms at an early stage in the drug development process. The recent developments in computational chemistry allow the prediction of possible polymorphic forms based only on the molecular structure of the drug. The Polymorph Predictor, from Molecular Simulations, is currently the only commercial software package that can predict the possible polymorphs of an organic compound from its molecular structure [51]. The package developed by Karfunkel and co-workers [52–54] uses a Monte Carlo simulated annealing approach to generate thousands of possible crystal packing alternatives for a given molecule. Each of the unique crystal structures is then subjected to a lattice energy minimization to obtain the relative stability ranking of the various packing possibilities and the resulting lowest-energy structures are the potential polymorphs. This method has been successfully employed to generate known polymorphs of paracetamol (Fig. 6A and B) and progesterone, starting from the molecular structures alone [55]. It has also been used to predict polymorphs for a range of small molecules and to predict unknown polymorphic structures of 4-aminodioxane glyoxyhydratase, a selective inhibitor of 5'-adenosylmethionine decarboxylase [56], and of aspirin [57].

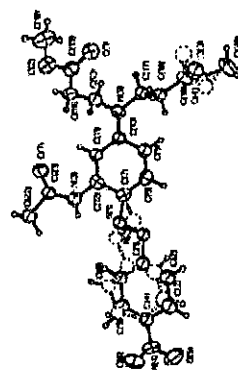


Fig. 5. ORTEP plots of the two molecular conformations (I and II) for the X-ray structure determination of 2'-acetyl-4'-[N,N-bis(2-methyl-1-propyl)amino]-4-nitroazobenzene (Scheme 1, Structure I at 293 K). Thermal ellipsoids are drawn at 50% probability, with non-hydrogen atoms being represented by the solid lines and hydrogen atoms by the dashed lines [48], reproduced with the permission of the American Chemical Society.

2.6. Directing the crystallization of specific polymorphs

Complementing the different computational methods for predicting the stable polymorphs of a given compound, various experimental methods are also being employed extensively to control the type of polymorph formed during the crystallization process. Many studies have reported the role of additives in controlling the outcome of the crystallization process. Some of the preselected additives are capable of inhibiting the nucleation and/or growth of the unwanted polymorphs. For the first time, the role of reaction by-products in controlling polymorph appearance of a drug has been reported [59]. This drug is sulfathiazole that is known to exist as polymorphs, forms I, II, III and IV, that differ in the hydrogen-bond network. Form I was found to be different from the other three forms as a result of a different hydrogen bonding at the amine moiety of the molecule. From studies of the hydrogen-bonding pattern, it was predicted that the ethanido derivative of sulfathiazole could selectively control the formation of form I over other forms by ensuring the growing face of form I without disrupting the structure (Fig. 7A). Because a similar effect was not possible with the other forms, incorporation of the ethanido derivative in the other forms should inhibit their growth (Fig. 7B). Experimentally, it was shown that the ethanido by-product stabilized form I over the other polymorphs. This study clearly shows that the combination of crystal morphology and the hydrogen-bond network analysis of the different polymorphs offer a new and powerful approach to understanding and controlling polymorph appearance and stability in the presence of additives.

A similar approach was also applied to stabilize a metastable conformational polymorph of 2-plutamic acid using additives [60]. Methods such as DREDDING and TRIPPOS force fields were used to select appropriate additives which could ensure the α and β conformations. Four additives were chosen for this study of which two were present exclusively in the β conformation and theoretically should selectively inhibit the crystallization of the β phase and thus stabilize the metastable α phase. Experimentally, it was proven that the additives, by virtue of their conformation, were able to selectively inhibit the

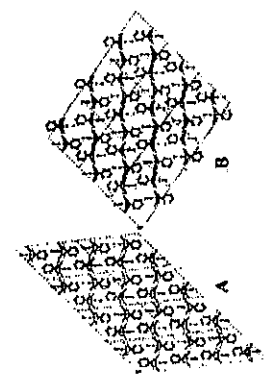


Fig. 6. Comparison of the crystal structure of paracetamol A (A) versus the most likely packing arrangement, Scheme 7 (B) [51], reproduced with the permission of Elsevier Science.

The theoretical predictions of lattice energies, entropies, morphologies and polymorphs should stimulate experimental activities and vice versa. The current crystal-modelling efforts have the potential of producing more quantitative tools for bridging structures and properties, which could help in crossing solid forms with desired properties [22]. There are many limitations in using computational methods for predicting polymorphs theoretically. The first limitation is that the ab initio screening is useful only for nonionic rigid molecules. For more complex systems, the method is very useful for generating plausible crystal structures, but it is not accurate enough to determine which of these possible structures can actually be crystallized [58]. In addition, the limitations in computer power can restrict the use of this method for predicting polymorphs of complex molecules. An issue of concern is that the existing methods only predict the lattice energies, which relate to internal energies or enthalpies of the crystals. However, the relative thermodynamic stability of polymorphs is determined by the Gibbs free energy, which is a linear function of both enthalpy and entropy. Predictions of the relative stability of polymorphs will be more accurate when the entropies, as well as lattice energies, are considered. Application of molecular dynamics may enable the entropies to be calculated. Hence, no general method is currently available for the prediction or interpretation of the properties of complicated polymorphic or pseudopolymorphic systems.

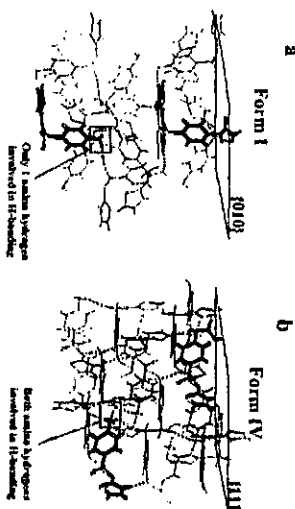


Fig. 7. Possible binding interaction of ribonucleoside in the D-loop growing faces of (a) form I and (b) form IV of valproic acid [19], reproduced with the permission of Elsevier Science.

appearance of the stable β polymorph of L-glutamic acid by interfering with either the nucleation rates or the growth rates and thus stabilize the metastable form. These studies demonstrate clearly that the molecular packing and intermolecular hydrogen bonds are the main features, which make possible the conformational discrimination. The use of conformational mimicry to stabilize the metastable structures of conformational polymorphs now offers a powerful tool for the prediction and development of robust processes for the control of polymorphic systems.

2.7. Characterization of polymorphs using a combination of analytical techniques

The common techniques often fail to differentiate definitively between two structurally similar polymorphs. Hence more advanced techniques or a combination of techniques need to be used to avoid errors of interpretation and in the identification of polymorphs [24]. Combinations of techniques are being employed currently for the characterization of crystalline pharmaceutical solids. For example, conventional single-crystal X-ray diffraction and polarized microscopy were of no use in distinguishing the two forms I and II of roxibam, a very promising cardiovascular drug, because of the relatively small crystallite sizes of the polymorphs. Hence, transmission electron microscopy (TEM) and

synchrotron X-ray diffraction techniques were employed to characterize the unit cells of the two forms. By coupling the highly resolved synchrotron powder X-ray diffraction data shown in Fig. 8, with in-

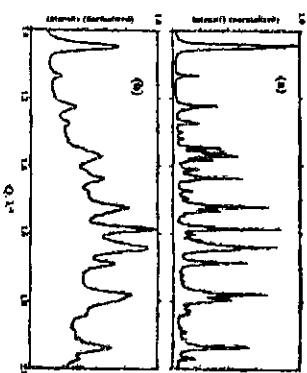


Fig. 8. A comparison of (a) a synchrotron pattern of polymorph II of roxibam, collected using a wavelength of 0.0006 Å with (b) a conventional X-ray diffraction pattern using CuK α radiation in a region where there are many overlapping peaks. The patterns are plotted as a function of $2\theta = 2\pi d \sin \theta / \lambda$ to remove the effects of different wavelengths [81], reproduced with the permission of the American Pharmaceutical Association.

formation obtained from TEM diffraction patterns, the unit cell parameters of the two forms of roxibam were determined [61]. Similarly, the three modifications, I, II and III, of the nonsteroidal antiinflammatory drug, tiaprofenic acid, could not be distinguished by the two traditional spectroscopic methods, FTIR and ^{31}P -NMR spectroscopy. The modifications can only be distinguished by a combination of thermodynamic and powder X-ray diffraction methods [62].

Another example, to which a combination of techniques has been successfully applied to identify the various conformational polymorphs of a drug, is the characterization of the solid forms of neostane [29]. Neostane, *N*-(3,3-dimethylbutyl)-1- α -aspartyl-4-phenylalanine methyl ester, a new high-potency sweetener exists in the following phase-pure crystalline forms: monohydrate, the most stable crystalline form of neostane under ambient conditions, a methanol + water solvate [63], a methanol solvate [64], an amorphous anhydride [29] and a crystalline anhydride (form A, [65]). The authors conducted a systematic study of the conversion of the anhydride under vacuum to a mixture of anhydride forms followed by the reconversion of the anhydride to the monohydrate upon exposure to moisture under ambient conditions. No significant changes were observed in the powder X-ray diffraction patterns during part of the reconversion process, suggesting that no change in lattice structure had occurred. However, the solid-state ^{13}C -CP-MAS NMR spectra, indicated the presence of several forms of neostane during the reconversion (Fig. 9). This discrepancy in the results between the two techniques was attributed to the conformational change of neostane molecules during reconversion, without significant change in unit cell parameters. This example indicates that both solid-state ^{13}C -CP-MAS NMR spectroscopy and powder X-ray diffraction are needed to analyze mixtures of solid forms of conformationally flexible molecules, such as neostane.

A combination of solid-state ^{13}C -NMR spectroscopy and single crystal X-ray diffraction also has been used to examine the solid-state tautomerism of acetohexamide [66,67]. Polymorphism of the antidiabetic drug acetohexamide has been investigated by numerous techniques. On the basis of FTIR data, form A of acetohexamide has been proposed to exist

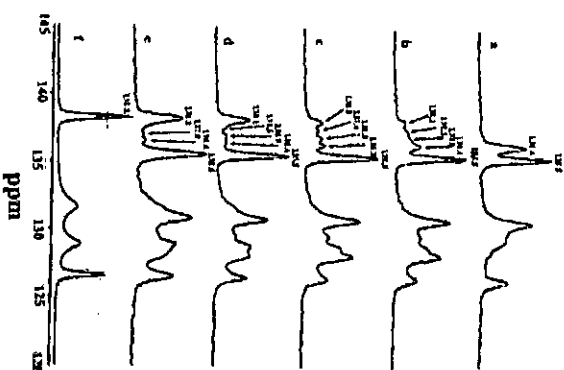


Fig. 9. Resonance signal of the phenyl carbon (C-15) recorded in the solid state in the ^{13}C -CP-MAS NMR spectra of neostane anhydride: (a) sample generated by placing the original anhydride under vacuum (~ 1 Torr) for 3 days; (b–d) sample after being sealed in a jar for 2, 4, 6 and 8 days, respectively; (e) sample after being exposed to a relative humidity environment of 65% for 12 days [29], reproduced with the permission of the American Chemical Society.

in the enol-tautomeric state, whereas form B has been proposed to be in the keto-tautomeric state. Using NMR and crystal structure data it was firmly established that both these acetohexamide polymorphic forms are present in the keto-form. Hence the combination of solid-state NMR spectroscopy and X-ray crystallography provided strong evidence that both forms of acetohexamide exist in the keto-tautomeric state and are truly polymorphic.

3. Recent advances in the identification and characterization of hydrates and solvates

3.1. Introduction to solvates and hydrates

It has been estimated that approximately one-third of the pharmaceutically active substances are capable of forming crystalline hydrates [68]. The water molecule, because of its small size, can easily fill structural voids and because of its multidirectional hydrogen bonding capability, is also ideal for linking a majority of drug molecules into stable crystal structures [2]. The mere presence of water in a system is not a sufficient reason to expect hydrate formation, because some compounds, though they are soluble in water, do not form hydrates. It is the activity of water in the medium that determines whether a given hydrate structure will form. Solvates may be formed when a pure organic solvent or a mixture of solvents is used as the solvent for crystallizing the compound. Gaultory [69] has discussed the various methods of preparation of hydrates and solvates in detail. Because solvates behave similarly to hydrates, common analytical techniques can be used for characterization of solvates and hydrates.

3.2. Structural aspects

Crystalline hydrates, based on their structure may be classified into three categories. The first category (class 1) are the isolated site hydrates, where the water molecules are isolated from direct contact with other water molecules by intervening drug molecules, e.g., cephradine dihydrate. The second category (class 2) are channel hydrates where the water molecules included in the lattice lie next to other water molecules of adjoining unit cells along an axis of the lattice, forming channels through the crystal, e.g., ampicillin trihydrate. The channel hydrates can be subdivided into two subcategories. One category comprises the expanded-channel or nonstoichiometric hydrates, which may take up additional moisture in the channels when exposed to high humidity and for which the crystal lattice may expand or contract as the hydration or dehydration proceeds effecting changes in the dimensions of unit cells, e.g. cromolyn sodium. The other subcategory comprises

the planar hydrates, which are channel hydrates in which water is localized in a two-dimensional order, or plane, e.g. sodium thiopropen. The third category (class 3) of crystalline hydrates are the ion-associated hydrates, in which the metal ions are coordinated with water, e.g., ethidolol calcium [8,9].

In this section, some examples of nonstoichiometric hydrates and their characterization will be discussed in detail because these forms pose a special challenge in dosage form development due to unpredictable change in water content in the crystals. Following the work of Cox et al. [70] the unusual water uptake and formation of nonstoichiometric hydrates of cromolyn sodium was reinvestigated using single crystal X-ray diffraction, PXRD, as well as by molecular modeling [71]. Cromolyn sodium, an antihistaminic drug, exists as two liquid crystalline phases and a crystalline hydrate phase that sorts and liberates water continuously and reversibly to give a continuous range of nonstoichiometric hydrates [70]. The changes in the PXRD patterns of the crystalline hydrate phase of cromolyn sodium in response to the surrounding relative humidity (RH) were explained in the light of the molecular and crystal structure of cromolyn sodium. Single crystal X-ray diffraction indicated the space group for cromolyn sodium as $P1$, a chiral space group, even though the molecule itself is achiral. The crystal structure of cromolyn sodium with five or six water molecules per cromolyn sodium molecule, solved at room temperature by Hamodrakas et al. [72], revealed the positions of only one sodium ion and two water molecules and showed that the second sodium ion and the other water molecules are disordered. Recently, the single crystal structure of cromolyn sodium at 70% RH, with 6.44 molecules of water was solved at 173 K by Chen et al. [71]. This work showed that the second undetermined sodium ion is disordered over three sites and that four of the eight water positions are partially occupied. Comparison of the crystal structures determined by Hamodrakas et al. [72] and Chen et al. [71] indicated that the cromolyn anion is flexible. In particular, the bond and torsional angles of the 2-hydroxypropoxy linking the two cyclic moieties, charged to accommodate lattice expansion or contraction resulting from water sorption and desorption by the crystals. As water is taken up, the relative occupancies of the sites of the

second sodium ion and that of water molecules change. As a result, the unit cell structure with $a = 90^\circ$ approaches the monoclinic form with $a \neq 90^\circ$. To summarize, the presence of large water channels, the flexibility of the 2-hydroxypropoxy link, the disorder of the second sodium ion (Fig. 10) and the disorder of the surrounding water molecules in the crystal lattice explain the reversible and nonstoichiometric water sorption and desorption by cromolyn sodium. This study emphasizes the importance of the detailed single crystal structure in explaining many unusual physico-chemical properties of drug hydrates.

The muscarinic agonist, LY297802 tartrate (i.e., (+)-3-[3-(butylthio)-1,2,5-triazol-4-yl]-1-azabicyclo[2.2.2]octane monohydrate), was also found to exhibit an unusual tendency to form nonstoichiometric hydrates of variable, but specific composition, ranging from 0 to 0.5 mol of water [73]. Solid-state ^{13}C -NMR spectroscopy, in conjunction with moisture sorption analysis and X-ray crystallography was used to provide unique insights into nonstoichiometric moisture sorption behavior. The PXRD patterns of the drug exposed to different RH values (0 to 75%), indicated neither a peak shift nor the presence of any new peaks, suggesting that

the anhydrous and the hydrated forms of the drug are isomorphous. Fig. 11 shows the significant changes in the SSNMR peaks on exposure to different relative humidities and temperature, indicating that water incorporated into the crystal lattice changes the local chemical environment and causes the observed NMR changes. The incorporation of water into the crystal lattice of the drug was also confirmed by X-ray crystallography. The considerable hygroscopicity of the drug was rationalized in terms of the similar crystal structures of the hydrated and nonhydrated forms, and hence no significant structural modifications are needed for the reabsorption of water into the solids. The rates of dehydration and rehydration are largely determined by the size of the water channels and the strength of the hydrogen-bonding interactions that bind the water molecules in the channels.

Another interesting study with different solvates of L-lysine monohydrochloride (LH) was conducted by Bandyopadhyay et al. [74]. LH was found to form a pure methanol solvate at water activity, $a_w < 0.34$, with methanol activity, $a_m > 0.7$; a dihydrate at $a_w > 0.65$ with $a_m < 0.45$, and mixed solvates at intermediate values of a_w and a_m . It was found that the dihydrate and the mono-

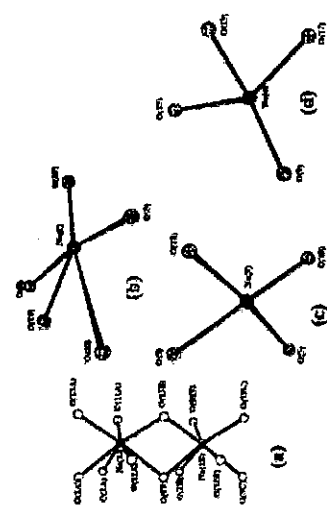


Fig. 10. In hydrated cromolyn sodium, coordination environment of (a) the first partially occupied sodium ion, Na(1), shows in two neighboring water molecules (b) the second partially occupied sodium ion, Na(2), (c) Na(3), and (d) Na(4). The diagram illustrates the arrangement of sodium ions and water molecules within the crystal lattice, with some sites being partially occupied. The diagram is reproduced with the permission of the American Pharmaceutical Association.

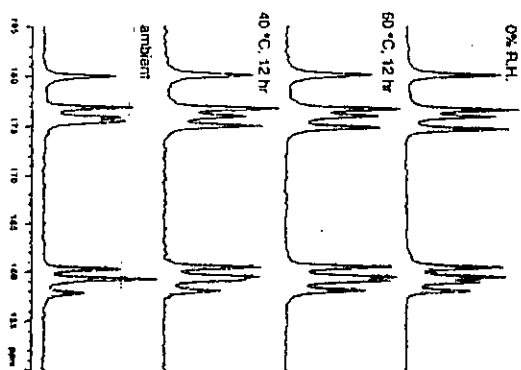


Fig. 11. Solid-state ^{13}C -NMR spectra of LY291036 in various states: (—) 0% RH, (---) 60 °C, 12 hr, (·····) 40 °C, 12 hr, and (—) ambient. The compound was prepared as a monohydrate (after storage at 0% humidity and before and after drying at elevated temperatures (73) and equilibrated with the permeation of the American Pharmaceutical Association).

methanol solvated forms of LH possessed similar crystal structures, similar PXRD patterns, but differed in the crystal habit. The crystal structures of LH hydrate and methanol solvate indicate that one molecule of methanol in the methanol solvate occupies approximately the same volume as the two water molecules in the dihydrate. During dehydration in the presence of methanol in the crystallization medium, the loss of one or more water molecules from the crystal lattice was compensated by the gradual uptake of methanol into the crystal structure to satisfy the hydrogen bonding pattern within the lattice with minor rearrangements, giving rise to mixed solvates. The similarities of the crystal lattices of the dihydrate and monomethanol solvate explain the similarity of the PXRD patterns.

3.3. Phase transformation of hydrates and solvates

Phase changes due to hydration/dehydration and solvation/desolvation of pharmaceutical compounds during processing or in the final product may result in an unstable system that would affect the bioavailability of drug from solid dosage forms. Various types of phase changes are possible in solid-state hydrated or solvated systems in response to changes in environmental conditions, such as relative humidity, temperature and pressure. For example, some hydrated compounds may convert to an amorphous phase upon dehydration and some may convert from a lower to a higher state of hydration yielding forms with lower solubility. Alternatively, a kinetically favored but thermodynamically unstable form may be converted during pharmaceutical processing to a more stable and less soluble form [8]. The phase transitions in hydrates and solvates can occur at various stages of dosage form development. Morris [9] has discussed the behavior of hydrates during processing, handling and storage of formulations in detail.

The phase transformations associated with exposure to water, such as during solubility measurements, wet granulation processes, dissolution studies and accelerated stability tests are likely to occur via solution-mediated. Solution-mediated phase transformations depend upon the solution phase to provide the mobility necessary to rearrange in the most stable form and hence are much faster than solid-state transformations. The rate of a solution-mediated transformation is proportional to the solubility of the species involved. Temperature, pressure and relative humidity may increase the rate of phase transformation of hydrates by increasing mobility in the system.

Solution-mediated phase transformations have been reported for many hydrate systems, such as theophylline crystals [17], epinephrine mesylate [75] and neddoroniol sodium [76]. Ghosh and Ghatak [77] have addressed a common problem associated with the characterization of solvates which centers around the determination of solubilities of solvates and of non-solvates that undergo phase transformation in the presence of an interesting solvent, such as solvation of non-solvates in the solvent of crystallization or the desolvation of solvates in water. A thermodynamic cycle analogous to Hess's law but based on free

energies has been developed to predict the theoretical solubilities of 1,2-dialkyl-3-hydroxy-4-pyridones, which form 1:1 formic acid solvates in the presence of formic acid, and of the 1:1 formic acid solvates which produce the corresponding unsolvated compounds in the presence of water. A good correlation was obtained between the solubility values measured by the standard extrapolation method and that calculated by means of the thermodynamic cycle.

Apart from identifying and characterizing the phases during various stages of drug development, it is very important to gain an understanding of the dehydration/hydration mechanisms and kinetics. Many models have been developed to account for the dehydration kinetics of the crystalline hydrates [78]. Nucleation is the most significant phenomenon in determining the transformation kinetics, that is, the rate of formation of a new phase [8]. The dehydration kinetics to some extent will also depend upon the class of the hydrate system to which the drug belongs, particle size and morphology. The practical applications of understanding the dehydration kinetics, as indicated by Morris [9], are mainly the determination of the conditions for allowable exposure of bulk drug substances during development and processing, proper packaging, allowable temperature ranges for shipping, storage, and labeling of the final product, and the initial selection of a form for development.

3.4. Prediction of the formation of hydrates and solvates

Predicting the formation of solvates or hydrates of a compound and the number of molecules of water or solvent incorporated into the crystal lattice of a compound is complex and difficult. Each solid compound responds uniquely to the possible formation of solvates or hydrates and hence generalizations cannot be made for a series of related compounds. Certain molecular shapes and features favor the formation of crystals without solvent; these compounds tend to be stabilized by efficient packing of molecules in the crystal lattice, whereas other crystal forms are more stable in the presence of water and/or solvents. There may be too many possibilities so that no computer programs are currently available

for predicting the crystal structures of hydrates and solvates.

3.5. Characterization of hydrates and solvates

The common methods for the characterization of hydrates and solvates are polarized light microscopy and hot stage microscopy, DSC, TGA, Karl Fischer titrimetry, single-crystal X-ray diffraction, powder X-ray diffraction, and infrared spectroscopy. These methods have been reviewed in detail [21] and will also be discussed in detail in later chapters.

Pressure DSC is gaining increasing popularity in the study of solvates and hydrates where dehydration reactions occur above or near the boiling point of water. Using conventional DSC, it is very difficult to measure the heat of dehydration and heat of vaporization separately, but if one conducts DSC experiments at elevated pressures, the two processes may be completely separated. The advantage of using pressure DSC is that the pressure can be precisely controlled and the solids can be subjected to a controlled temperature program while under substantially elevated temperatures. The influence of elevated pressures on the solid-state behavior of carbamazepine dihydrate was studied by Han and Suryanarayana [79]. In Fig. 12 it is shown that pressure DSC can separate the dehydration and vaporization endotherms of carbamazepine dihydrate during its conversion to the anhydrous form. Also the technique permitted the water liberated on dehydration to remain in intimate contact with the anhydrous phase formed which could significantly influence its solid-state properties.

The combined physical analytical techniques of thermogravimetry and infrared spectroscopy (TG/IR) can permit identification of the solvent incorporated into the crystal lattice. This combined technique has been used to study formulated products, such as capsules and tablets [80].

4. Current challenges and future directions

4.1. Origins of the challenges

A series of flow charts and decision trees have been presented and discussed [11,22] that can be

water uptake then had been reported previously for other crystalline samples of aspirin under similar conditions. Various possibilities were suggested for the unusual water uptake of aspirin on roller compaction, such as formation of a polymorphic form of aspirin with a much greater affinity for water, formation of a crystalline hydrate in the aspirin sample, or significant reduction in particle size of the aspirin particles thereby providing an increased specific surface area for water vapor absorption. It is also possible that roller compaction disrupted the crystalline order of some part of the aspirin crystals forming amorphous regions, which then take up relatively large quantities of water into their bulk structure. This example clearly indicates that processes, such as roller compaction, can introduce considerable disorder in the surface of crystals leading to a marked increase in the tendency to adsorb water vapor.

Thermal activation, like mechanical activation during processing, also results in a high-energy state of crystals that may reorganize into a different lattice arrangement resulting in a phase change. The chemical stability of drug substances is important, because formulations are often dried at elevated temperatures after wet granulations so that the tablets may contain small regions of high temperature (hot spots) during compression. Various examples have shown that a change of temperature may influence the stability of drug molecules [16]. The effect of low temperatures, such as during freeze-drying, on the crystalline form of the drug has also been studied. The formation of a new monohydrate hydrate during freeze-drying has been reported [85]. The formation of a crystalline hydrate by an excipient during freeze-drying may have several practical consequences, such that the difficulty of removing bound water from the crystal lattice can significantly limit the drying rate, while the residual water that is not removed by freeze-drying may be a potential threat to product stability if it is released during storage. The monohydrate hydrate formed during freeze-drying survived the typical drying cycle and converted to the anhydrous polymorph of mannitol upon heating.

Spray drying has also been shown to lead to loss of crystallinity in materials, by a combination of processes involving rapid solidification of dissolved material and solid-state transitions due to milling effects in the slurry. Spray drying leads to conver-

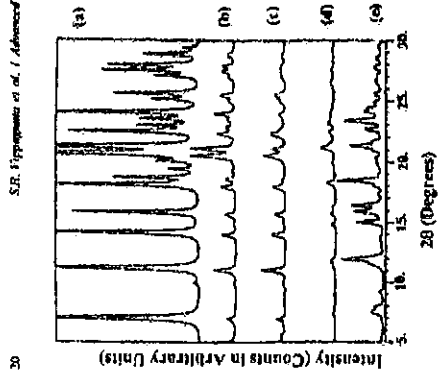


Fig. 11. Powder X-ray diffraction patterns of aspirin: (a) theoretical powder pattern calculated from the crystal structure of aspirin; (b) experimental powder pattern of the aspirin; (c) experimental powder pattern of the aspirin after roller compaction; (d) experimental powder pattern of aspirin after roller compaction followed by annealing at 160°C; (e) experimental powder pattern of aspirin after roller compaction followed by annealing at 160°C. The experimental powder pattern of aspirin after roller compaction followed by annealing at 160°C is reproduced with the permission of the American Pharmaceutical Association.

suggested that the trauma to crystals during grinding may lead to a decrease in crystallinity, which should improve the compression capacity and dissolution rate of the drug molecules. This hypothesis was tested by studying the morphology, crystalline state, compression capacity and dissolution properties of native and ground crystals of aspirin and lactose monohydrate [83]. No significant increase in compression capacity was observed when native and ground crystals were compared. Only a slight increase in the dissolution rate was observed for ground aspirin crystals which was attributed to surface defects due to grinding resulting in improved crystal wetting.

The effect of roller compaction on lattice defects and phase change has been examined for aspirin [84]. The water vapor sorption isotherm obtained for aspirin on roller compaction indicated much more

ent), and the issues of disappearing polymorphs and the appearance of new polymorphs in the following sections we will address some of these issues and some of the studies that have addressed these problems.

4.2. Phase transformations during processing

The effects of pharmaceutical processing on the crystalline state of drug polymorphs and solvents have been discussed recently by Brittain and Fiese [16]. Exposure to changes in temperature, pressure, relative humidity and comminution are encountered during processes such as drying, granulation, milling and compression. The stresses applied to crystals during pharmaceutical processing can cause defects in their crystal lattices, and contribute to lattice disorder, thus affecting the physical properties of the resulting powder [81]. This problem has been discussed in detail by Byrn et al. [10]. Arising from different degrees of crystalline disorder, the difficulty in reproducing materials with the same properties is a major concern in the pharmaceutical industry.

Milling, the last processing step in the production of bulk drug substance to reduce particle size, is often accompanied by a decrease in crystallinity due to the creation of lattice defects, beginning at the surface. The defects created by mechanical activation of the solid on the surface can migrate, transform, and change their number and nature. If the defects in the mechanically activated crystal lead to produce a crystal lattice different from the initial lattice, then a polymorphic transformation has taken place. Milling-induced polymorphic changes have been observed for many small drug molecules, such as fentanyl, chloramphenicol palmitate, indomethacin and phenylbutazone [16]. Polymorphic transformation of the dipeptide sweetener, aspartame hemihydrate, can occur during milling [82]. Polymorph II of aspartame hemihydrate was found to transform to form I during ball-milling or on heating for 30 min at 160°C in the presence of steam as shown in the X-ray diffraction pattern (Fig. 13). The susceptibility of form II of aspartame hemihydrate to transform to form I has been attributed to the less symmetric crystal structure of form II compared to that of form I as studied by spectroscopic methods.

Some authors, such as Hiltner [81] have

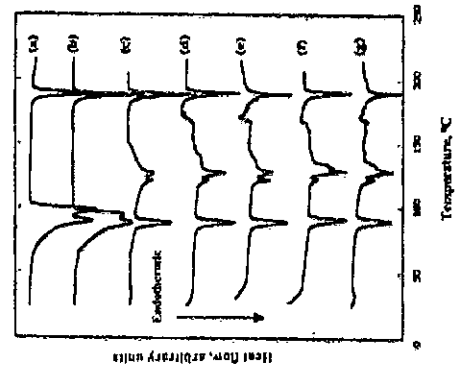


Fig. 12. DSC thermograms of aspartame hemihydrate: (a) aspartame hemihydrate; (b) aspartame hemihydrate after roller compaction; (c) aspartame hemihydrate after roller compaction followed by annealing at 160°C; (d) aspartame hemihydrate after roller compaction followed by annealing at 160°C; (e) aspartame hemihydrate after roller compaction followed by annealing at 160°C; (f) aspartame hemihydrate after roller compaction followed by annealing at 160°C. The experimental powder pattern of aspirin after roller compaction followed by annealing at 160°C is reproduced with the permission of Elsevier Science.

used by investigators to characterize the polymorphs and solvents of compounds under development or for registration with regulatory authorities. Due to the complex and nonconventional behavior of various organic drug molecules, there are many opportunities for research and development in the area of characterization of polymorphs and solvents. Some of the problems which are commonly encountered during characterization of crystalline solids and which need to be addressed are: disorder in the crystal lattice due to pharmaceutical processing leading to conversion of a crystalline phase to an amorphous material or phase conversion from one form to the other; quantifying the amount of single polymorph in a mixture of polymorphs; identifying the solid form of the active ingredient in the formulated product, particularly when the drug is a minor component in the presence of numerous other materials (excipi-

sion of a crystalline phase to an amorphous state and, because the amorphous state is measurable with respect to the crystalline form, phase transformations are likely to occur within the shelf life of the pharmaceutical product, resulting in loss of quality and potency in the product [86].

In view of the significant effects that the state of disorder in crystalline solids caused by pharmaceutical processing can have on the properties of pharmaceutical solids, it is important to be able to assess the extent of disorder in a solid quantitatively down to very low levels. Various methods have been used to measure the percent disorder, such as using predetermined mixtures, measurements of X-ray powder diffraction, density and heats of crystallization which revealed limits of detectability down to about 10%. Using water vapor sorption measurements under very carefully controlled conditions, it was possible to detect disorder as low as 1% in milled samples of sucrose [87]. A comparison of the four methods mentioned above for estimating the percent disorder of milled samples of sucrose gave very consistent results, once the underlying factors that make these techniques sensitive to the concentration of amorphous content were recognized and taken into account.

4.3 Degree of crystallinity

The previous section has emphasized that many pharmaceutical processes lead to a decrease in crystallinity of drug phases. Various studies have concluded that the formation of amorphous material during processing is highly undesirable. The amorphous material, being in a thermodynamically metastable state, is susceptible to reversion to the crystalline state, affecting many physico-chemical characteristics of the drug. A later chapter provides detailed coverage of amorphous materials. An estimation of the degree of crystallinity of a sample before and after processing poses one of the larger challenges facing the pharmaceutical field. Powder X-ray diffractometry is still the commonly used method for determining the degree of crystallinity, though this method suffers from some limitations due to peak broadening, amorphous halo, and preferred orientation which make interpretation and quantization difficult. DSC may not be a sensitive method for measuring crystallinity due to crystalliza-

tion of the amorphous content at elevated temperatures and the effects of differences in heat capacity. Solution calorimetry has been proposed as an accurate method for analysis of percent crystallinity [11,88,89]. A decrease in the endothermic enthalpy of solution indicates a decrease in the crystallinity of the sample. However, differences in surface area produced by grinding or by other processing techniques can also result in changes in the heat of wetting of a sample. Judicious choice of solvent can be employed to reduce such surface effects, which themselves contribute to the observed crystallinity of the sample.

Near infrared (NIR) spectroscopy is another technique being used to measure the degree of crystallinity, and has also proved useful in studies of the polymorphism and water content of sugars. The NIR spectrum of a sample contains both physical and chemical information. Being noninvasive, nondestructive and operable at room temperature, the method is a valuable tool with which to assess changes in the amorphous and crystalline state of lactose [90]. NIR has been used to follow the changes in the amorphous state, the onset of crystallization, and the changes between α - and β -lactose, which accompany the onset of crystallization. In another study, the nucleation and crystallization kinetics of amorphous lactose was investigated by gravimetry in an automated vacuum moisture balance. The combination of isothermal and nonisothermal activation energies allowed the investigation of both crystal growth and nucleation mechanisms and led to the separation of activation energies for nucleation and growth [91].

4.4 Characterization of mixtures of polymorphs

Another common problem encountered during drug development is quantitative control of the proportion of polymorphic forms present in a mixture. According to the US FDA regulations, the method of analysis for the proportion of forms must be validated, and also the proportion of forms must remain within stated limits through the rest of the shelf life of the product. This is a very onerous requirement, especially if the forms have a tendency to interconvert. Bynn et al. [11] suggested that the best way to deal with this problem is probably by

developing methods to prepare only one crystal form and maintaining this form throughout processing. Powder X-ray diffractometry is often a useful method to determine the percentages of polymorphs in a mixture. However, the detection limit is variable from case to case, and is sometimes as high as 15%. It is therefore important to develop sensitive analytical methods with a lower limit of detection.

Attenuated total reflectance (ATR) FTIR spectroscopy has been shown to be valuable for the quantitative analysis of the polymorphic content of bulk pharmaceutical materials. The feasibility of using ATR-FTIR for the qualitative and quantitative analysis of mixtures of pharmaceutical polymorphs has been studied using three known polymorphs of gliclazide as a model compound [92]. Definitive identification and quantitation of all three polymorphs could be achieved using ATR-FTIR spectroscopy in conjunction with partial least-squares modeling. This technique has many advantages, such as speed, nondestructiveness, relative ease of use, and most important, no sample pretreatment before measurement.

Raman spectroscopy is another technique that is being widely used to quantitatively estimate the percentage of one polymorph in a mixture of polymorphs. FT-Raman spectroscopy offers many advantages, the most prominent being, minimal sample preparation, sensitivity to polymorphism, and noninterference from water. Two polymorphs of fluconazole were characterized using FT-Raman spectroscopy and principal components regression using cross validation provided quantitative analysis of the percentage of one polymorphic form in the mixture of other forms [93]. A novel sample holder was developed whereby the sample is held in an NMR tube which is rotated around its axis and at the same time moved up and down. This method of sample presentation leads to a large increase in the volume scanned and is important for inhomogeneous samples for which sub-sampling is a problem. Possible degradation of the sample through heating by the laser can also be avoided [94].

X-Ray powder diffractometry is still the common method for the quantitative estimation of polymorphs in a mixture of polymorphs. This method requires that at least one high-intensity peak unique to each form is available for intensity measurements and that

the plot of the peak intensity ratio as a function of the weight ratio of the components should result in a straight line. Modern computer controlled X-ray powder diffractometers now permit quantitative analysis of multicomponent mixtures using the complete powder diffraction profile rather than a limited amount of low-angle integrated intensity data. Artificial neural networks (ANNs) in quantitative X-ray powder diffractometry were used successfully to identify and quantify the two known modifications of ranitidine hydrochloride even when the weight fraction of one polymorph in the mixture was as low as 0.01 [95]. ANNs have been used mostly in problems of pattern recognition and modeling, and is therefore useful in deciphering the pattern in diffraction data from polymorphic mixtures. The ANN model predicted concentrations precisely, accurately, and with minimal bias through a wide range of ratios of the two known ranitidine hydrochloride polymorphic forms in a mixture (Fig. 14). This method minimizes the problems associated with preferred orientation and overlapping X-ray lines. The same group of researchers has shown the potential of ANNs in combination with DSCIT spectroscopy to analyze the polymorphic purity of crystalline ranitidine hydrochloride as a bulk drug and as an active ingredient of

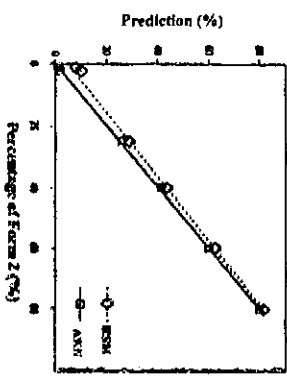


Fig. 14. Predicted concentrations of the two polymorphic forms (Form 1 and 2) of ranitidine hydrochloride by the artificial neural network (ANN), a statistical modeling method, and by the artificial neural network (ANN) method. Predicted versus actual percentage of Form 2 (95%), compared with the percentage of Ranitidine Hydrochloride.

a tablet formulation. Simultaneous identification and quantification of all the ingredients in the tablet formulation was possible. This study has shown that the complex problem of quantifying a drug in mixtures containing two or more components with overlapping spectra can be solved by the DRIFT-ANNS technique [96].

Another technique, which is gaining popularity in the quantitative analysis of mixtures of polymorphs, is solid-state ^{13}C -CP-MAS NMR spectroscopy. This method was preferred for quantitative analysis of polymorphic mixtures of the benzilide, penicillamine, which exists as two polymorphs with different colors and crystal habits [27]. ^{13}C -NMR provided the most sensitive and definitive evidence of the transition from the yellow to the orange form. This method enabled us to find as little as 2% of orange penicillamine in a sample consisting mostly of the yellow polymorph. It is the least invasive of the instrumental methods and can be used to detect the ratio of the two polymorphs in solid formulations.

A related challenge faced by the pharmaceutical industry is the determination of the polymorphic nature of the drug in the presence of excipients in a dosage form especially when the active drug is present as a low percentage of the overall formulation [97]. This problem can be addressed by developing sensitive techniques with lower limits of detection or by using a combination of techniques.

5. Conclusions

In order to save time and cost it is very important to choose the most suitable form of the crystalline drug in the initial stages of drug development. In recent years a good deal of research has been directed towards achieving this goal. Systematic isolation and early characterization of the largest number of possible forms of a drug reduces the chances of surprises at the late production stage due to identification of a new crystalline form or phase change. With the development of more sophisticated computational tools, the main focus of many investigators is to be able to predict all the possible forms of a drug from its molecular structure. Understanding the origins of the multiple solid forms of a drug

molecule, either due to differences in packing arrangement or conformation of the molecule, becomes the first step in prediction. Single crystal X-ray diffraction and solid-state NMR spectroscopy are two techniques that are gaining increased application in determining the various crystal structures and the origins of polymorphism and pseudopolymorphism of a particular drug. When crystal structures can be calculated with certainty, it will be possible to predict the various polymorphs of a compound and this information could be used to guide experimental studies. This goal may be difficult to achieve owing to the complex molecular structures of new organic molecules and the presence of several molecules in each asymmetric unit, but the future development of improved force fields and increased computational speeds may make it achievable.

Improved experimental methods leading to more accurate and detailed phase diagrams are also finding increased use in determining the stability of various polymorphs. It is important to make every effort to prepare and to identify the most stable polymorph in order to guide the selection of the optimal form for development. The emergence of sensitive methods and the use of combination techniques, facilitate the identification and the more accurate characterization of the various polymorphs of a drug molecule. One of the main analytical challenges faced by the pharmaceutical industry is the development of better quantitative methods for identifying a single polymorph in a mixture of polymorphs and for determining the percentages of amorphous or crystalline content of the drug. More and more sensitive methods are being developed to address this problem.

An increased understanding of the phenomenon of polymorphism should enable pharmaceutical scientists to gain control over the crystallization process in order to selectively obtain the desired polymorph or suppress the growth of an undesired one. Phase changes during processing and scale-up are a problem, which may be avoided by carefully designed initial small-scale studies. The availability of detailed structural data, combined with strategic design of substrates and additives, has led to significant advances in the control over the polymorphs obtained in a particular crystallization [98]. With all the information available from these initial studies, it

should be possible to design and to select processing conditions which would give a desired polymorph and maintain the desired form throughout the various stages of drug processing and manufacture.

References

- [1] H.G. Brittain, S.R. Byrn, Structural aspects of polymorphism, in: H.G. Brittain (Ed.), *Polymorphism in Pharmaceutical Solids*, Vol. 9, Marcel Dekker, New York, 1995, pp. 73–124.
- [2] S.R. Byrn, R.R. Pfeiffer, J.G. Sewell, Solid-State Chemistry of Drugs, SSCI, West Lafayette IN, 1999.
- [3] T. Hahn (Ed.), *International Tables for Crystallography*, International Union of Crystallography, Dordrecht, 1997.
- [4] M. Kikuchi-Bandaru, Thermochromism in the Analysis of Pharmaceuticals, Pergamon, Oxford, 1971.
- [5] L. Borka, J.K. Hachisima, Crystal polymorphism of pharmaceuticals, *Acta Pharm. Japad.* 40 (1990) 71–93.
- [6] L. Borka, Review on crystal polymorphism of substances in the European Pharmacopoeia, *Pharm. Acta Helv.* 66 (1991) 16–22.
- [7] D. Glaze, Thermal analysis and calorimetric methods in the characterization of polymorphs and solvents, *Thermochim. Acta* 248 (1995) 1–39.
- [8] K.R. Morris, N. Rodriguez-Hernandez, in: J. Swarbrick, J.C. Boylan (Eds.), *Encyclopedia of Pharmaceutical Technology*, Vol. 7, Marcel Dekker, New York, 1993, pp. 393–441.
- [9] K.R. Morris, Structural aspects of hydrates and solvents, in: H.G. Brittain (Ed.), *Polymorphism in Pharmaceutical Solids*, Vol. 9, Marcel Dekker, New York, 1995, pp. 125–181.
- [10] S.R. Byrn, R.R. Pfeiffer, G. Suprenant, D.W. Grant, N.B. Grimes, Solid-state pharmaceutical chemistry, *Chem. Mater.* 6 (1994) 1118–1138.
- [11] S. Byrn, R. Pfeiffer, M. Guery, C. Henberg, G. Pochalska, Pharmaceutical solids: a strategic approach to regulatory considerations, *Pharm. Res.* 12 (1995) 935–954.
- [12] D.W. Grant, Theory and origin of polymorphism, in: H.G. Brittain (Ed.), *Polymorphism in Pharmaceutical Solids*, Vol. 9, Marcel Dekker, New York, 1995, pp. 1–33.
- [13] J.K. Hachisima, W.C. McCone, Pharmaceutical applications of polymorphism, *J. Pharm. Sci.* 38 (1949) 911–929.
- [14] W.I. Higuchi, P.K. Law, T. Higuchi, J.W. Shul, Polymorphism and drug availability, Solubility relations in the methylprednisolone system, *J. Pharm. Sci.* 52 (1963) 150–153.
- [15] M.J. Narasimhan, S. Doshi, D.W. Grant, J.H. Ryting, Properties of solids that affect transport, in: G.L. Amidon, P.L. Lee, E.M. Topp (Eds.), *Transport Processes in Pharmaceutical Systems*, Vol. 102, Marcel Dekker, New York, 2000, pp. 375–611.
- [16] H.G. Brittain, E.F. Fies, Effects of pharmaceutical processing on drug polymorphs and solvents, in: H.G. Brittain (Ed.), *Polymorphism in Pharmaceutical Solids*, Vol. 9, Marcel Dekker, New York, 1995, pp. 331–341.
- [17] N. Rodriguez-Hernandez, D. Lopez-Ballinas, H.J. Wu, Phase transitions and heterophase/epitaxial nucleation of hydrated and solvates of theophylline crystals, *Int. J. Pharm.* 85 (1992) 149–162.
- [18] N. Rodriguez-Hernandez, D. Murphy, Significance of conformational crystallization mechanisms and kinetics in phase-transition systems, *J. Pharm. Sci.* 84 (1995) 651–660.
- [19] J.W. Alkhatib, Crystallization, Bousworth-Hillman, Oxford, 1993.
- [20] M.C. Ester, Encoding and decoding hydrogen-bond patterns of organic compounds, *Acc. Chem. Res.* 23 (1990) 128–136.
- [21] H.G. Brittain, Methods for the characterization of polymorphs and solvates, in: H.G. Brittain (Ed.), *Polymorphism in Pharmaceutical Solids*, Vol. 9, Marcel Dekker, New York, 1995, pp. 227–278.
- [22] L. Yu, S.M. Rezak, G.A. Suprenant, Physical characterization of polymorphic drugs: an integrated characterization strategy, *Sci. Pharm.* 1 (1998) 118–127.
- [23] H.G. Brittain, Spectral methods for the characterization of polymorphs and solvates, *J. Pharm. Sci.* 86 (1997) 403–412.
- [24] D. Glaze, Thermal analysis, microcalorimetry and conductance techniques for the study of pharmaceuticals, *J. Therm. Anal. Cal.* 56 (1999) 1283–1308.
- [25] H.G. Brittain (Ed.), *Physical Characterization of Pharmaceutical Solids*, Vol. 70, Marcel Dekker, New York, 1995.
- [26] R. Berman, The role of modulated temperature differential scanning calorimetry in the characterization of a drug molecule exhibiting polymorphic and glass forming behavior, *Int. J. Pharm.* 135 (1996) 43–53.
- [27] P.C. Shuckla, R. Godfrey, P. Hachcock, R. Marshall, P.C. Shuckla, S. Regan, A.P. Walz, Crystal polymorphism in pharmaceuticals is driven by electronic delocalization and changes in intermolecular hydrogen bonding. A crystallographic, spectroscopic and computational study, *J. Chem. Soc., Perkin Trans. 2* (1998) 2061–2071.
- [28] D.C. Appledy, R.A. Flinn, R.K. Harris, R.W. Luzzano, S. Teverez, T.L. Threlkell, Soluble polymorphs enabled by single-angle spinning NMR, *J. Pharm. Sci.* 88 (1999) 1275–1280.
- [29] B.E. Padden, M.T. Zell, Z. Ding, S.A. Schroeder, D.W. Grant, E.J. Messon, Comparison of solid-state ^{13}C -NMR spectroscopy and powder X-ray diffraction for analyzing mixtures of polymorphs of nortriptyline, *Anal. Chem.* 71 (1999) 3325–3331.
- [30] J. Smith, E. MacNassar, D. Borch, T. Sackhoff, S. Byrn, Application of two-dimensional ^{13}C -solid-state NMR to the study of conformational polymorphisms, *J. Am. Chem. Soc.* 120 (1998) 11700–11713.
- [31] M.L. Ely, H. Altmeyer, M.J. Kaufman, Selection of optimal polymer/solvent forms of a benzilide derivative for acid drug development, *Pharm. Dev. Technol.* 4 (1999) 81–87.
- [32] A. Burger, R. Ruchberg, On the polymorphism of pharmaceuticals and other molecular crystals, *J. Theory of Biomolecular Crystals*, Acta [Wisc] II (1979) 237–271.
- [33] A. Burger, R. Ruchberg, On the polymorphism of pharmaceuticals and other molecular crystals, II. Applicability of thermodynamic rules, *Makromol. Chem. [Wisc] II* (1979) 277–316.

- [34] J. Hancock, M. Kuhnert-Groshäuser, Demonstration of the lattice compatibility and consistency in polymorphous esterase crystallized by Ruediger et al., *J. Pharm. Sci.* **88** (1999) 165-168.
- [35] L. Yu, Inferring thermodynamic stability relationships of polymorphs from melting data, *J. Pharm. Sci.* **84** (1995) 966-974.
- [36] S. Todorov, An open-ended approach to drug polymorphism, *Thermochim. Acta* **352** (1996) 73-79.
- [37] G.U. Kulmacs, P. Kumaradas, C.N.R. Rao, Charge density study of the polymorphs of p-nitrophenol, *Chem. Mater.* **10** (1998) 3108-3109.
- [38] D. Siegel, P.V. Marschal, L. Steudel, P. York, Solid-state characterization of chloridazepoxide polymorphs, *J. Pharm. Sci.* **87** (1998) 655-662.
- [39] N. Bhagavan, K.J. Davey, H.F. Leckman, L. Williams, R. Payne, R. Roberts, R. Bower, R. Docherty, Crystal chemistry and solvent effects in polymorphic systems—nicotinic acid, *Chem. Soc. Faraday Trans. 9* (1993) 1035-1041.
- [40] M.R. Chari, M. Zandi, T. Powell, A. Gazzaniga, F. Goodson, Structural characterization of two polymorphic forms of benzenic phosphine, *J. Pharm. Sci.* **87** (1998) 1638-1644.
- [41] M. Yokota, H. Iwakura, Y. Okada, Structural analysis of two crystal forms of nicotinic acid, *Synthetic Metals*, *Bull. Chem. Soc. Jpn.* **72** (1999) 1731-1736.
- [42] L. Yu, G.A. Segremon, C.A. Marshall, C.A. Russell, S.V. Senek, J.J. Bowyer, T.B. Boeckel, J.G. Sawell, S.R. Byrne, Thermodynamics and conformational polymorphism of a benzoylcarboxylic crystal system, *J. Am. Chem. Soc.* **122** (2000) 585-591.
- [43] G.A. Segremon, T.B. Boeckel, S.R. Byrne, J. Bowyer, C.A. Russell, S.V. Senek, L. Yu, Conformational and color polymorphism of 5-methyl-3-(4-dimethylamino)-3-thienylbenzoic acid, *J. Pharm. Sci.* **84** (1995) 1385-1386.
- [44] R.D. Starkey, M.L. Demerit, molecular models and solid state kinetics: the non-transition model, *J. Pharm. Sci.* **85** (1997) 1234-1236.
- [45] S.S. Long, B.E. Padua, E.J. Munson, D.W. Grant, Solid-state solubility studies of model dipeptides: arginine and aspartate hydrochloride, *J. Pharm. Sci.* **86** (1997) 64-71.
- [46] M.I. Yoshida, K. Takahashi, Y. Ohsaka, T. Yoshizawa, N. Furukawa, M. Ueda, Combination of hydrogen bonds to equilibrium and transition of neocortin, *J. Phys. Chem. A* **103** (1999) 2773-2775.
- [47] A. Schacht, S. Katsuya, M. Appel, S. Kirsch, M. Baumhöfer, Y. Eschen, Measuring the temperature widths of a first-order single crystal to single crystal phase transition using solid-state NMR: Application to the poly(morphism) of 3-(4-chlorobenzoyl)-D-serine/threonine, *J. Am. Chem. Soc.* **121** (1999) 11281-11289.
- [48] G. McKerrig, R.K. Harris, A.S. Bazzano, A.V. Chaudhry, J.P. Champagne, J.F. Brinkley, Z. Guo, Analysis of a solid-state conformational rearrangement using ¹³C-NMR and X-ray crystallography, *J. Phys. Chem. A* **103** (1999) 3550-3513.
- [49] H. Thawalla, Y. Suzuki, Y. Nishii, H. Shimada, R. Shimada, Pressure effect on phase transitions in hexachloro benzene crystals, *Bull. Chem. Soc. Jpn.* **72** (1999) 381-387.
- [50] A. Itaru, Y. Suzuki, Y. Nishii, H. Shimada, R. Shimada, Temperature and pressure induced phase transition in hexachloro-1,4-squaraine: crystal, *Bull. Chem. Soc. Jpn.* **72** (1999) 963-969.
- [51] K. Nakamura, Polymorphic predictions, *Modern Drug Discovery* **3** (2000) 55-57.
- [52] R.J. Gietz, H.R. Kunitz, F.J. Lyons, The prediction of x-ray diffraction molecular crystal structures by solving the packing problem, *J. Med. Graph.* **11** (1975) 275-276.
- [53] H.R. Kunitz, R.J. Gietz, No test prediction of possible crystal structures for general organic molecules, *J. Comp. Chem.* **13** (1992) 1111-1183.
- [54] H.R. Kunitz, F.J. Lyons, Practical aspects of predicting possible crystal structures on the basis of molecular information only, *Springer* **6** (1992) 43-50.
- [55] R.S. Payne, R.J. Roberts, R.C. Rowe, R. Docherty, Examples of successful crystal structure prediction: polymorphs of phenol and polystyrene, *Int. J. Pharm.* **177** (1999) 231-245.
- [56] H.R. Kunitz, Crystal packing calculations and Rietveld refinement in elucidating the crystal structures of two modifications of 4-amidinobenzoic guanidinehydrazide, *Acta Crystallogr.* **B55** (1996) 555-561.
- [57] R.S. Payne, R.C. Rowe, R.J. Roberts, M.H. Cantow, R. Docherty, Thermal polymorphs of zephin, *J. Comp. Chem.* **20** (1999) 255-273.
- [58] P. Verwer, F.J.J. Lovens, Computer simulation to predict possible crystal polymorphs, in: S.B. Liepinskas, D.B. Boyd, G.M. Rotstein, in: *Computational Chemistry*, Vol. 12, Wiley-VCH, New York, 1996, pp. 377-385.
- [59] N. Bhagavan, K.J. Davey, R. Howe, R. Roberts, Disrupting polymorphism: the role of reagent byproducts: the case of salicylic acid, *Int. J. Pharm.* **172** (1998) 169-177.
- [60] R.J. Davey, N. Bhagavan, G.D. Frost, R. Docherty, Polymorphism in molecular crystals: stabilization of a metastable form by conformational interplay, *J. Am. Chem. Soc.* **119** (1997) 1767-1777.
- [61] Z.G. Li, R.L. Hawton, C.M. Fox, H. Lu, P. Mc, R.D. Vickers, M.B. Martin, B.H. Toby, Polymorphic determination for the CPD DB/ITE stereoisomer, nifedipine, using a combination of electron diffraction and synchrotron X-ray powder diffraction techniques, *J. Pharm. Sci.* **88** (1999) 201-207.
- [62] A. Berger, K.T. Kohler, Polymorphism without IR- and Ramon-quasiperiodic differences: tetrapipecolic acid, dimer modification, *Pharmazie* **54** (1999) 361-366.
- [63] M. Goodman, R.H. Munson, P.G.A. Samiati, R. Lucchini, M. Santoro, E. Brandelli, X-Ray structures of some dipeptide ester hydrolysis, *J. Peptide Sci.* **4** (1997) 229.
- [64] Z. Ding, Young Jr., W.G. Padua, H.E. Schneider, S.A. Peterson, I. Makoski, E.J. Grant, D.W. Grant, Crystal structure and physical characteristics of racemic octadecyl stearate, *J. Chem. Crystallogr.* **29** (2000) 965-975.
- [65] Z. Ding, B.E. Padua, S.A. Schneider, E.J. Munson, D.W. Grant, Preparation and characterization of polymorphs of racemic octadecyl, AAOS Pharmacol. Symp. **1** (1999) 5-102, 2331.
- [66] P. Guo, Determination of the composition of dicarboxylic-acidic polymorphs and pseudopolymorph mixtures using ¹³C-CF₄-MAS NMR, *Pharm. Res.* **13** (1996) 1095-1104.
- [67] G.A. Segremon, R.R. Pfeiffer, R.R. S.R. Byrne, Solid-state investigation of the association of acetonitrile, *Int. J. Pharm.* **146** (1997) 93-99.
- [68] H.R. Stahl, The problems of drug interactions with excipients, in: D.D. Braizer (Ed.), *Toxicology of Drugs and Pharmaceutical Products*, Elsevier/North-Holland Biomedical Press, 1980, pp. 345-380.
- [69] K.J. Gietz, Generation of polymorphs, by drugs, solvents, and excipients solids, in: H.G. Bostian (Ed.), *Polymerization in Pharmaceutical Solids*, Vol. 95, Marcel Dekker, New York, 1999, pp. 183-220.
- [70] J.S.G. Cox, G.D. Woodard, W.C. McCrone, Solid-state chemistry of ceramide monomers (diacylglycerols), *J. Pharm. Sci.* **60** (1971) 1548-1665.
- [71] L.R. Chen, Y.G. Yeung, H. Li, D. Leung-Belknap, D.W. Grant, Solid-state behavior of ceramide monomers, *J. Pharm. Sci.* **88** (1999) 1191-1200.
- [72] S. Harwood, A.J. Godkin, B. Sheldrick, X-Ray study of dicarboxylic compounds, *J. Pharm. Pharmacol.* **36** (1973) 54-56.
- [73] S.R. Kundu, V.A. Raut, Origins of the unusual byproduct sequence observed in LY737002 synthesis, *J. Pharm. Sci.* **87** (1998) 1468-1471.
- [74] R. Banjagayakarn, R. Estlin, Y.G. Yeung, H. Li, D.W. Grant, Effects of water activity on recrystallized α -lactose monohydrate, in: *Proceedings of the World Congress on Particle Technology*, The Brighton Center, Brighton, 7-9 1998.
- [75] J. Sheng, G.M. Weiskopf, S.P. Dastis, D.W. Grant, Desorption behavior of polymers during dry-down, *J. Pharm. Sci.* **88** (1999) 1071-1078.
- [76] R. Chakrabarti, L. Chen, D.W. Grant, Physical characterization of molecular solution systems, *J. Pharm. Sci.* **87** (1998) 1052-1061.
- [77] S. Lang, D.W. Grant, Decomposition of the solubilities of crystalline solids in solvent media under static plastic changes: Solubilities of 12-hydroxy-3-oxododecanoic acid and other ketone and esters in toluene acid and water, *Int. J. Pharm.* **114** (1993) 182-196.
- [78] S.R. Byram, Solid-State Chemistry of Drugs, Academic Press, New York, 1982.
- [79] J. Elm, R. Suryanarayana, Applications of pressure differential scanning calorimetry in the study of pharmaceutical products, *I. Carbohydrate derivatives*, *Int. J. Pharm.* **157** (1997) 209-218.
- [80] C. Rodriguez, D.E. Bagby, Characterization of pharmaceutical solutions by combined thermogravimetric and reduced viscosity, *J. Pharm. Sci.* **86** (1997) 301-306.
- [81] R. Hirsinger, Molecular characterization in the field of modern drug formulation, *Adv. Pharm. Technol.*, Adv. Information Systems **5** (1997) 55-127.
- [82] S.S. Long, B.E. Padua, E.J. Munson, D.W. Grant, Solid-state characterization of two polymorphs of aspirin, *Int. J. Pharm.* **Sci. **87** (1998) 561-567.**
- [83] P. Ungemach, M. Böhm, A.M. Gaspert-Garcia, J.C. Gayé, Ground and native crystals: comparison of compressibility and dissolution rate, *Int. J. Pharm.* **170** (1999) 51-61.
- [84] B.C. Hancock, G. Zografi, Effects of solid-state processing on water uptake by aspirin, *J. Pharm. Sci.* **83** (1994)

- [62] G.A. Sarghianian R. B. S.R. Byrns, Solid-state intercalation of the unanionized form of aceto-bromazepam, *Int. J. Pharm.* 146 (1997) 91-99.
- [63] H.P. Stahl, The problems of drug interactions with excipients, in: D.D. Bitterman (Ed.), *Toxicity/Bio-Safety of Drugs and Pharmaceutical Products*, Elsevier/North-Holland Biomedical Press, 1989, pp. 365-385.
- [64] K.J. Gaultier, Generation of polymorphic hydrates and anhydrous forms, in: H.G. Brittain (Ed.), *Polymorphism in Pharmaceutical Solids*, Vol. 95, Marcel Dekker, New York, 1999, pp. 181-226.
- [65] J.S.G. Cox, G.D. Woodard, W.C. McCrene, Solid-state chemistry of cinnamyl sodium (disodium cinnamylsulfate), *J. Pharm. Sci.* 60 (1971) 1454-1455.
- [66] L.R. Chen, Y.G. Young, H. D. Leach, S.-B. Satterton, D.W. Grant, Solid-state behavior of cinnamyl sodium hydride, *J. Pharm. Sci.* 68 (1979) 1191-1200.
- [67] S. Hamada, A.J. Gadda, B. Stedrick, X-ray analysis of disodium cinnamylsulfate, *J. Pharm. Pharmacol.* 26 (1975) 54-56.
- [68] S.M. Rowell, V.A. Russell, Origin of the unusual hygroscopic behavior in LY737802 succinate, *J. Pharm. Sci.* 87 (1998) 1548-1571.
- [69] K. Bhandaryak, K. Ertan, Y.G. Young, H. D.W. Grant, Effects of water activity on monohydrated tri-*n*-butyl hydrochloride, in: *Proceedings of the World Congress on Pharm. Technology*, The Brighton Center, Brighton, 7-9 1996.
- [70] J. Sheng, Q.M. Westmark, S.P. Doshi, D.W. Grant, Desiccation behavior of epinephrine monohydrate, *J. Pharm. Sci.* 85 (1996) 1021-1035.
- [71] R. Ertan, L. Chen, D.W. Grant, Physical characterization of sublethal sodium hydride, *J. Pharm. Sci.* 87 (1998) 1051-1061.
- [72] S. Ghandi, D.W. Grant, Determination of the solubilities of crystalline solids, in solid form that induce phase changes: Solubilities of 1,2-diphenyl-3-benzoyl-4-phenylmethane and their kinetic and physical in water and water, *Int. J. Pharm.* 146 (1997) 81-96.
- [73] S.R. Byrns, Solid-State Chemistry of Drugs, Academic Press, New York, 1992.
- [74] J. Elm, R. Sarghianian, Applications of pressure differential scanning calorimetry in the study of pharmaceutical hydrates, *J. Calorimetry/Calorifics*, *Int. J. Pharm.* 157 (1998) 209-218.
- [75] C. Rodriguez, D.E. Bugh, Characterization of pharmaceutical solids by combined thermogravimetric and infrared analysis, *J. Pharm. Sci.* 86 (1997) 263-266.
- [76] R. Harnett, Molecular pharmacology in the hands of modern drug formulation, *Adv. Pharm. Technol.*, APV International, Sept. 6, (1993) 35-127.
- [77] S.S. Liang, B.E. Padua, E.J. Berman, D.W. Grant, Solid-state characterization of two polymorphs of aspartame, *Biotechnology, J. Pharm. Sci.* 87 (1998) 561-567.
- [78] P. Langemann, M. Joffe, A.M. Taylor-Thompson, J.C. Gray, General and specific crystallographic comparisons of con-
- [79] A. Salari, R.E. Young, Application of infrared weak reflectance FTIR spectroscopy to the analysis of mixtures of pharmaceutical polymorphs, *Int. J. Pharm.* 163 (1998) 157-169.
- [80] J. Xu, W. Jiang, Characterization of polymorphic forms of thiazolidine using Fourier transform Raman spectroscopy, *J. Pharm. Sci.* 86 (1997) 1438-1441.
- [81] F.W. Langkilde, J. Spohrer, L. Tschering-Hyatt, J. Mack, Quantitative FT-Raman analysis of two crystal forms of a pharmaceutical compound, *J. Pharm. Biomed. Anal.* 15 (1997) 581-596.
- [82] S. Aguilera-Astivia, F. Wu, T. Hader, D. Senise, I.G. Tschering, Powder diffractionless assay of two polymorphic forms of melastatin hydrochloride, *Int. J. Pharm.* 164 (1998) 107-114.
- [83] S. Aguilera-Astivia, I.G. Tschering, D. Senise, Solubility assay of melastatin HCl as a bulk drug and as active ingredient in tablet using DSCFT spectroscopy with anti-diffractional elements, *Pharm. Res.* 16 (1999) 1427-1432.
- [84] H.G. Brittain, Reciprocity in polymorphism, *Pharm. Technol.* 18 (1993) 50-53.
- [85] J. Berman, K.J. Dool, J. Mack, Concentrated polymorphs, *Algen. Chem. Int. Dev.* 18 (1999) 340-344.
- [86] K. Hader, J. Berman, B. Ganes, S.R. Elm, Synthesis of aspartame, a popular sweetener, *J. Adv. Chem. Ser.* 107 (1995) 4278-4287.
- [87] A. Salari, C. Albrecht, G. Ziegler, Assessment of disorder in crystalline solids, *Int. J. Pharm.* 170 (1999) 51-61.
- [88] B.C. Hancock, G. Ziegler, Effect of solid-state processing on water uptake by aspirin, *J. Pharm. Sci.* 83 (1994) 246-251.
- [89] L. Ye, N. Nelson, E.G. Graham, D.S. Milner, R.E. Wasylyuk, Evidence of a zwitterion hydrate during freeze-drying and product impurities, *J. Pharm. Sci.* 88 (1999) 196-198.
- [90] K.G. Ven. Sath, J.T. Chennu, Nucleation processes in crystalline sucrose systems, *Int. J. Pharm.* 58 (1990) 163-196.
- [91] A. Salari, C. Albrecht, G. Ziegler, Assessment of disorder in crystalline solids, *Int. J. Pharm.* 170 (1999) 337-347.
- [92] M.J. Pital, A.L. Lelak, J.E. Lang, K. Ganes, Quantitative crystallinity determination for nucleation analysis by solid-state calorimetry: correlations with solubility, *J. Pharm. Sci.* 67 (1978) 657-669.
- [93] H.G. Brittain, D.W. Grant, Effects of polymorphism and solid-state solvation on solubility and dissolution rate, in: H.G. Brittain (Ed.), *Polymorphism in Pharmaceutical Solids*, Vol. 94, Marcel Dekker, New York, 1999, pp. 279-353.
- [94] E. Vennemann, J. Harnett, A. Kettler, The use of near infrared spectroscopy to detect changes in the kinetics of amorphization and crystallization, *Int. J. Pharm.* 168 (1998) 231-241.
- [95] E.A. Sennett, D. Lin, G.Q.Z. Zhang, Nucleation and crystallization kinetics of hydrated cinnamyl succinate above the glass transition temperature, *J. Pharm. Sci.* 88 (1999) 291-296.
- [96] A. Salari, R.E. Young, Application of attenuated total reflectance FTIR spectroscopy to the analysis of mixtures of pharmaceutical polymorphs, *Int. J. Pharm.* 163 (1998) 157-169.
- [97] X.G. Wu, W. Jiang, Characterization of polymorphic forms of thiazolidine using Fourier transform Raman spectroscopy, *J. Pharm. Sci.* 86 (1997) 1438-1441.
- [98] F.W. Langkilde, J. Spohrer, L. Tschering-Hyatt, J. Mack, Quantitative FT-Raman analysis of two crystal forms of a pharmaceutical compound, *J. Pharm. Biomed. Anal.* 15 (1997) 581-596.
- [99] S. Aguilera-Astivia, F. Wu, T. Hader, D. Senise, I.G. Tschering, Powder diffractionless assay of two polymorphic forms of melastatin hydrochloride, *Int. J. Pharm.* 164 (1998) 107-114.
- [100] J. Berman, K.J. Dool, J. Mack, Concentrated polymorphs, *Algen. Chem. Int. Dev.* 18 (1999) 340-344.
- [101] K. Hader, J. Berman, B. Ganes, S.R. Elm, Synthesis of aspartame, a popular sweetener, *J. Adv. Chem. Ser.* 107 (1995) 4278-4287.